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UNIVERSITY OF ALBERTA

THE PETROLOGY, PALEONTOLOGY AND GEOCHEMISTRY OF THE CARSON CREEK NORTH REEF COMPLEX, ALBERTA.

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Petrology, Paleontology and Geochemistry of the Carson Creek North Reef Complex, Alberta , submitted by Eugene Millidge Leavitt B.Sc., M.Sc. in partial fulfilment of the degree of Doctor of Philosophy.

ABSTRACT

The Carson Creek North reef complex occurs in the subsurface of west-central Alberta, with an area of about 30 square miles and a maximum thickness of about 350 feet. The reef complex and the underlying reef platform form the Swan Hills Formation of the Beaverhill Lake Group of probable early Upper Devonian age.

Structure maps, isopach maps, and cross sections illustrate the atoll-like reef geometry and paleotopography. Stromatoporoids and algae were by far the most important reef organisms. Brachiopods, corals, and other fossils are common, but were not as important in governing reefal development. Many of the organisms, especially the stromatoporoids, appear to have been environmentally controlled, allowing the reef complex to be subdivided into seven biotopes each having distinctive biosomes.

Integrated data allow the reef complex to be divided into five facies, eleven microfacies, and thirty-two rock types. Geomorphic localities envisaged for the rock types vary from deep quiet water to shallow turbulent water to subaerial.

X-ray fluorescence analyses of more than 150 whole-rock samples and spectrophotometer analyses of 41 acid-soluble samples were carried out in a search for geochemical facies indicators; the elements analysed for were Sr, Ca, Mg, Mn, Fe, Al, Si, S and Ni. The results suggest that the various reef complex and off-reef facies are different geochemically. These variations can help determine the various reef environments, and should be useful in locating and interpreting the setting of similar reefs elsewhere.

The most important diagenetic features which have affected the reef-complex limestones are: biological diagenesis, cementation and lithification, neomorphism, solution, and fracturing; compaction and development of authigenic non-carbonate minerals are less important. In general, post-depositional diagenesis has not greatly altered the original sedimentary features.

The geological history of the reef complex has been portrayed as six major stages of development:

(1) Reef Platform Development - mild transgression and deposition of a biostromal type carbonate unit.

(2) Biohermal Development - more extensive transgression resulting in biohermal reef growth.

(3) Green Shale Development - major regression with subaerial erosion and solution of reefal carbonate.

(4) Bank Development - stability or mild transgression resulting in a calcarenite bank unit.

(5) Reef Death - regression and erosion of the reef resulting in termination of reef growth.

(6) Waterways Development - transgression and deepening of the water resulting in argillaceous non-reef sedimentation.

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CHAPTER 1 - INTRODUCTION

General

Carson Creek North oil field in west-central Alberta is an undolomited, atoll-like structure of early Upper Devonian age in the Beaverhill Lake Group. It was discovered in 1958 as a result of follow-up exploration to the triple discoveries in 1957 of the Swan Hills, Virginia Hills, and Kaybob reefoid oil fields. The stimulation of these latter three discoveries caused a renewed interest in the subsurface Devonian reefs in Alberta, as the Beaverhill Lake Group had been unproductive up to 1957.

Out of more than a dozen productive reefs (Swan Hills Formation) in the Beaverhill Lake Group, the Carson Creek North field was chosen for this thesis study for the following reasons:

(1) The field was penetrated to varying depths by over 40 wells, most of which had core and logging data which were available to the writer.

(2) The limestones of this reef are not dolomitized or altered to any extent, thus fossils and primary features are generally still evident and recognizable.

(3) It is a relatively small reef complex, yet it contains all the rock types and features found in larger and more widespread reefs.

The following report is based on petrological, paleontological, and geochemical data derived from the various rock types making up the complex.

Objective

The purpose of this study is to describe and give an environmental interpretation of the various microfacies within the reef complex. It attempts to evaluate variations in the biological, lithological, geochemical, and textural characteristics between microfacies in terms of paleoecology, reef development, processes of sedimentation, environment of deposition, and diagenetic alteration.

It also attempts to answer a number of specific questions which existed in the mind of the writer, namely:-

(1) Is Carson Creek North a true reef complex, a bank, a bioherm, or a biostrome?

(2) What is the distribution of organisms throughout the complex and are any forms restricted to a specific ecological niche?

(3) What are the different types of stromatoporoids present and can they be used as indicators of environment?

(4) How important are organic agencies in the formation of micrite or calcisiltite?

(5) What were the energy conditions and relative water depths during deposition of the various rock types?

(6) How does the Carson Creek North reef complex compare with modern reefs?

(7) Are there geochemical differences between the microfacies, and if so, can these be used to correlate within the complex, to indicate position in the reef, or to help determine the conditions of sedimentation?

(8) Were parts of the reef complex above water; was it ever subject to subaerial erosion; and what brought the reef-building episode to a close?

Though the thesis is not intended to be a purely economic one, it has applications to oil exploration. It is believed that some of the findings can be used in a comprehensive exploration program searching for similar structures elsewhere.

Method of Study

During the summer of 1964, the writer spent two months logging, studying, and analysing cores from the Redwater reef complex. This core was made available for study by Imperial Oil Enterprises, Ltd. in Edmonton. Klovan's (1964) excellent study was used as a guide for familiarization with the gross aspects of reef facies. Thirty samples from his Redwater cores were analysed for seven different oxides in a preliminary geochemical investigation. Research was started on the Carson Creek North reef complex in the fall of 1964.

Electric logs of all the wells penetrating the Carson Creek North reef complex, and core where available, were examined to locate tops and markers (see Table 8, Appendix 1). This gave the outline, extent, and shape of the bioherm and permitted the construction of isopach and structure contour maps.

Core was studied at the Socony Mobil Oil Company storehouse in Edmonton,

at the Oil and Gas Conservation Board Corehouse in Calgary, and at the University of Alberta in Edmonton. Slabbed core from 13 wells was studied in detail. Only the discovery well (6-1-62-12W5) has slabbed core available from the entire Beaverhill Lake - Gilwood Sand interval. Most of the other wells were cored down to, or slightly below, the oil/water interface (approximately - 5780').

The laboratory work consisted for the most part of examination of the slabbed core under the stereo-microscope after coating with mineral oil, and, in some cases, after polishing and etching. Though most of the rock types can be recognized using the stereo-microscope; thin-sections, acetate peels, and plexiglass peels were prepared where it appeared necessary in order to see finer and more subtle features. Staining of polished specimens and thin sections was done to distinguish between dolomite and calcite and to clarify certain textures. Examples of the fauna and flora were examined and identified where possible; peels or thin sections of more than 100 stromatoporoid specimens were studied.

Finally, more than 150 samples were prepared and analysed for eight different elements by x-ray fluorescence. In addition, 41 samples were dissolved in acetic acid and both the insoluble content and certain trace elements in the acid-soluble portion were determined.

Previous Work

Fewer detailed studies have been published on the subsurface Devonian reefs of Alberta than one might expect considering their economic importance. No attempt is made here to give a complete historical review of reef studies in Alberta but a few

of the papers that have proven most useful to the writer in the present investigation are mentioned below. For a more complete summary of reef studies in Alberta the reader is referred to Geological History of Western Canada (1964), Jenik (1965), and Mountjoy (1965).

Andrichuk (1958) and Klovan (1964) published studies that have become outstanding references on reefs in western Canada. These works give detailed ecological and facies analyses of Leduc age reefs, especially the Redwater reef complex. Mountjoy (1965) studied the exposed Miette reef complex of Leduc age in Jasper National Park.

The following have made important contributions to the knowledge of Beaverhill Lake age reefs. Fong (1959; 1960) named and described the producing unit of the Beaverhill Lake Formation, the Swan Hills Member. Edie (1961) studied the Swan Hills field and concluded that it consisted of a "buildup" of successively smaller atoll-like layers. Fischbuch (1962), in studying the Kaybob reef, came to the conclusion that stromatoporoids could be used to delimit depositional environments or zones. Murray (1964) completed a detailed study of the Judy Creek field, including not only the Swan Hills Formation, but also a reconstruction of the paleoenvironment of the surrounding off-reef Waterways Formation. Jenik (1965) did a detailed paleofacies study of the small Goose River field.

Terminology Used

The common terms used in association with carbonate buildups or "reefs" have for many years had a variety of meanings. This conflicting usage of terms has

perhaps caused more problems here than in any other single group of genetically associated rocks. As pointed out by Nelson, et al., (1962) this varied usage has led to misunderstanding among geologists and probably misinterpretation as to the origin of many of these structures. Because of this disagreement, it is necessary that every author closely define his terms in order to avoid further confusion. It should be emphasized, however, that were possible, existing definitions and terms should be used rather than inventing new ones to further clutter up an already burdensome nomenclature.

The terms and definitions used in this study are similar to those used by Nelson, et al., (1962) and Klovan (1964), namely:

Reef Complex - the aggregate of reef limestones and genetically related carbonate rocks (Henson, 1950).

Reef - a skeletal limestone deposit composed primarily of organisms possessing the ecologic potential to erect a rigid, topographic structure in the zone of wave action.

Organic-Reef - that portion of the reef which is or was built directly by organisms and is responsible for the reef's wave-resistant character.

Bank - a skeletal limestone deposit formed by organisms which do not have the ecologic potential to erect a rigid, wave-resistant structure.

Bioherm - reeflike, moundlike, lenslike, or otherwise circumscribed structures of strictly organic origin embedded in rocks of different lithology.

Biostrome - purely bedded structures, such as shell beds, crinoid beds, coral beds, et cetera, consisting and built mainly by sedentary organisms, and not swelling into moundlike or lenslike forms.

Following the above definitions, the Carson Creek North structure studied in this report is considered to be a biohermal reef complex.

The writer follows Nelson, et al., (1962) in stressing that the terms bioherm and biostrome should classify deposits only on the basis of the present day shape in the stratigraphic sequence. The terms reef and bank are used when the origin, or the ecologic potential of the organisms responsible, is considered. The major drawback of this proposal is that in the case of most ancient reefs, such as the Devonian reefs of Alberta, we are dealing with individuals or groups of organisms such as the stromatoporoids, many of the corals, and brachiopods, et cetera, that are now extinct. It is thus difficult to assess, with any degree of certainty, the exact nature and ecologic potential of these forms when they were living. This problem is greatly diminished, however, if all the information available from the rocks is utilized, and the Principle of Uniformitarianism applied. Despite the presence of many now extinct forms, the application of the principle "the present is the key to the past" is the most important tool in the interpretation of these ancient reef complexes.

CHAPTER 2 - REGIONAL SETTING AND STRATIGRAPHY

Location and Status

The Carson Creek North reef complex lies in the subsurface of west-central Alberta near Whitecourt, about 100 air miles northwest of the city of Edmonton (see Figure 1). It occurs at the southern end of the northeast trending Swan Hills - Judy Creek - Carson Creek chain of Beaverhill Lake reef complexes and was discovered in 1958 by Mobil Oil of Canada, Ltd.

The biohermal buildup above the so-called reef platform is fairly small and is oblong in shape. The bioherm measures about 8 by 4 miles at the base and is contained within townships 61 and 62 and ranges 11 and 12 W5M. The maximum thickness of this buildup above the platform is about 350 feet. Considerable reef section is believed to have been lost through solution and erosion.

At the present time the Carson Creek North reef complex is a producing oil and gas field. Because of a relatively extensive green shale horizon within the buildup, the operators have been allowed to consider the structure as containing two separate oil pools or accumulations. These are generally designated within the industry as the Carson Creek North Beaverhill Lake "A" and "B" Pools. There is some production from all of the wells that have penetrated the biohermal buildup. The regional dip in the area is about 40 feet per mile in a south-westerly direction and the oil-water interface occurs at an elevation of approximately -5780 feet. Drilling on the structure has been carried out on a spacing of two wells per square mile.

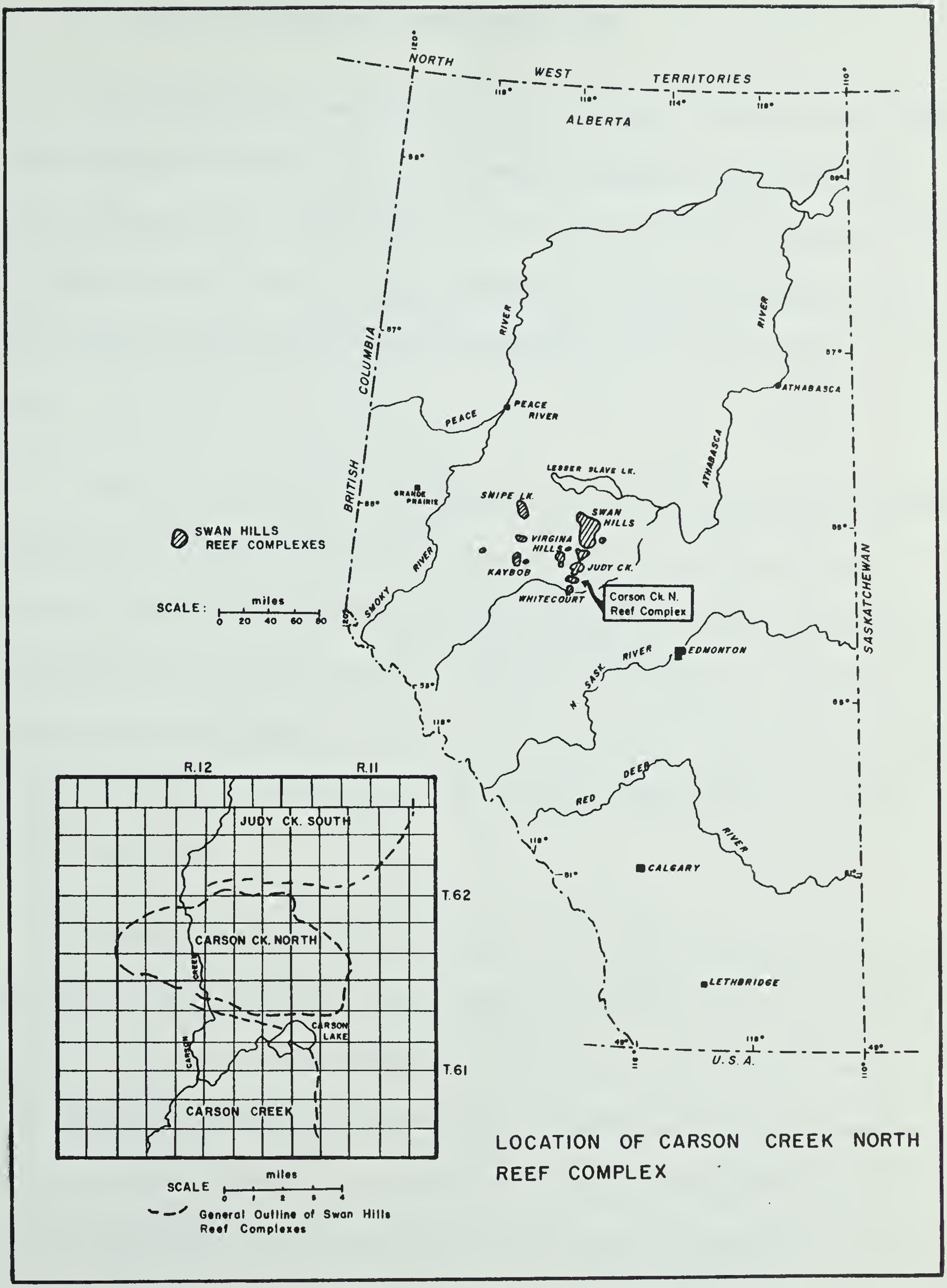


Figure 1. Location of Carson Creek North Reef Complex

Regional Stratigraphy, Correlation, and Age

The present study is restricted largely to the Carson Creek North reef complex and contributes little to the somewhat confused stratigraphic correlations of the Beaverhill Lake Group. A brief discussion on the subject is, however, given. Also it is proposed that a new stratigraphic classification for the units in question be set up in light of their economic importance and lithological variation in the Swan Hills area.

The regional setting and paleogeology of the Carson Creek North reef complex is illustrated in Figure 2. The Swan Hills reef complexes are situated along the margin of a broad carbonate platform or shelf that was very extensive in southwestern Canada and northwestern United States. These thick shelf deposits to the south of the platform edge consist largely of dense limestones, dolomites, and evaporites. North of the platform, the carbonate facies passes into shales and argillaceous limestones of the basinal facies.

The Peace River Arch was an emergent land mass during Beaverhill Lake time and parts, at least, of the Western Alberta Ridge are believed to have been positive as well. The present limit (see Figure 2) of the Beaverhill Lake Group to the east is not the limit of sedimentation. A large part, or possibly all, of the Precambrian shield was covered by seas at this time; this is evidenced by the Beaverhill Lake isopachs approaching the pre-Cretaceous erosional edge in that direction.

Table 1 shows the formational equivalents of the Beaverhill Lake Group, in going from the evaporite facies in the south to the shale rocks in northern Alberta.

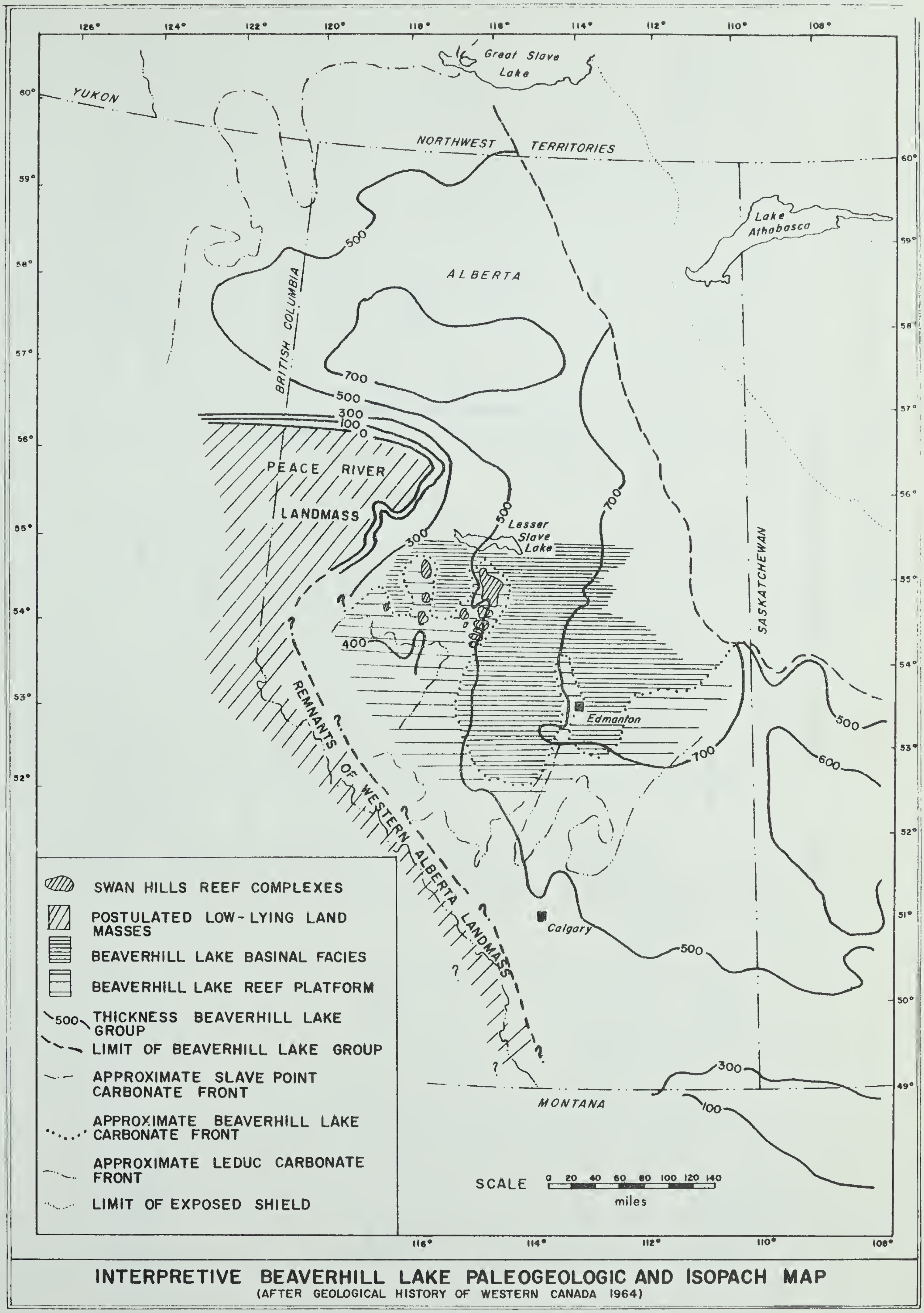


Figure 2. Interpretive Beaverhill Lake Paleogeologic and Isopach Map

NORTHEASTERN BRITISH COLUMBIA, NORTHWESTERN ALBERTA, SOUTHERN DISTRICT OF MACKENZIE	GREAT SLAVE LAKE AREA, AND NORTHEASTERN ALBERTA	NORTHEASTERN ALBERTA, NORTHWESTERN SASKATCHEWAN	WEST CENTRAL ALBERTA	EAST CENTRAL AND SOUTHERN ALBERTA	SASKATCHEWAN, MANITOBA, MONTANA, NORTH DAKOTA
Fort Simpson Formation	Hay River Formation	Waterways Formation Mildred Mbr	Beaverhill Lake Formation Mildred Mbr Swan Hills Mbr light brown unit	Beaverhill Lake Formation Mildred Mbr	Duperow Fm
		Moberly Mbr	Moberly Mbr	Moberly Mbr	Souris River Formation
		Christina Mbr	Christina Mbr	Christina Mbr	
		Calumet (Calmut) Mbr	Calumet (Calmut) Mbr	Calumet (Calmut) Mbr	
		Firebag Mbr	Firebag Mbr	Firebag Mbr	
		Livock River Formation	Slave Point Member dark brown	Basal limestone	
Horn River Fm Slave Point Formation	Slave Point Fm Fort Vermilion Mbr	Slave Point Fm Fort Vermilion Mbr	Fort Vermilion Mbr		
Watt Mountain-Sulphur Point Formation	Watt Mountain Formation	Elk Point Group	Elk Point Group	Elk Point Group	First red beds Dawson Bay Fm

TABLE 1 - TABLE OF FORMATION NAMES

(Geological History of Western Canada, 1964, p. 60)

Correlation across the western Canada basin is difficult for a number of reasons, a few of which are the following:

(1) Correlation must be made between surface and subsurface sections.

(2) Different names, type sections, and boundaries are often used for surface and subsurface areas.

(3) Correlation and boundaries in the subsurface have largely been based on lithologic changes, whereas in outcrop areas the units are more biostratigraphic in nature.

(4) The change from evaporites to shelf carbonates to reef complex to basinal shales presents the problem that the distribution of many and probably most of the organisms used in correlation was governed more by environment than by time.

(5) Depending on the type of fossils used, different workers often arrive at different ages for the same stratigraphic unit.

Despite these difficulties and differences of opinion, it is generally agreed that the Beaverhill Lake Group is correlative with the Souris River Formation to the south and southeast; the Waterways Formation to the northeast; parts of the Hay River, Fort Simpson, and Slave Point Formations to the north and northwest; and part of the Flume Formation to the west.

The type section for the Beaverhill Lake Formation occurs 55 miles southeast of Edmonton (Anglo-Canadian Beaverhill Lake No. 2 well, 11-11-50-17W4M). The unit here is 722 feet thick, consists of three alternating shale and fragmental

limestone units and was defined in 1950 by the Geological Staff of Imperial Oil Limited. In this area, the Beaverhill Lake rests disconformably on the Elk Point Group and grades upwards into the overlying Cooking Lake Formation (Fong, 1960).

In the Swan Hills area, the Beaverhill Lake Group averages about 500 feet, some 200 feet thinner than in the type section, and the three fragmental limestones are no longer recognizable. Here, reefal carbonates, enclosed in off-reef argillaceous limestones, dominate the lithology. These reefoid complexes were named the Swan Hills Member by Fong (1960) with the type section being designated in the well, Home Regent "A" Swan Hills 10-10-67-10W5M.

Warren (1933) introduced the term Waterways Formation, for a well and outcrop section 405 feet thick in northeastern Alberta at McMurray. Crickmay (1957) subdivided the Waterways Formation into 5 members at the Bear Biltmore No. 1 well (7-11-87-17W4M). Norris (1963) suggested that the Bear Biltmore well with its 701.5 foot thick Waterways section be used as the type section. Murray (1964; 1965) proposed that the term Waterways be used in the Swan Hills area and that Beaverhill Lake be dropped. Murray's reasons for the change are in the writer's opinion legitimate, but the change itself is neither practical nor desirable. The term Beaverhill Lake has become established for the designated unit in the Swan Hills area, and the amount of confusion a change would cause does not warrant it.

Farther to the north and northwest, the Beaverhill Lake Group and Waterways Formation can be correlated on logs with the lower parts of the Hay River and Fort Simpson Formations (Geological History of Western Canada, 1964). Also, the Slave Point Formation of northeastern British Columbia is correlated with the lower part of

the Beaverhill Lake Group (Griffin, 1965). In the oil industry, the Swan Hills reef platform or Dark Brown Member is often referred to as the "Slave Point Equivalent".

Finally, to the west, in the Rocky Mountains, Patterson (1955) suggested that the Flume Formation was equivalent to the upper part of the Beaverhill Lake Group (see Clark and Ethington, 1965). This correlation has been somewhat substantiated by faunal comparisons of Belyea (1957), McLaren (1962), Mountjoy (1965), and others.

Although stratigraphic correlations of the Beaverhill Lake Group have been attempted, the exact age of the units in question is still very much in doubt. Warren in 1933 compared the fauna of the Waterways with that of the Snyder Creek Shale in the United States and concluded it was of early Upper Devonian age. Many later workers have agreed with this correlation, whereas, others have compared the fauna to the older Cedar Valley Limestone and concluded it to be of late Middle Devonian age. Norris (1963) summarized the previous age assignments and tentatively assigned the Waterways to the early Upper Devonian.

The Slave Point Formation of northeastern British Columbia is considered to be Middle Devonian in age (Norris, 1963). This does not mean, however, that the Swan Hills reef platform is necessarily Middle Devonian. Since the Slave Point is considered to be the basal unit of a transgressing sea from the northwest, it is probably considerably older to the north than its facies equivalents in central and southern Alberta. Thus the reef platform in the Swan Hills area may be of either late Middle or early Upper Devonian age. Loranger (1965), in her study of northeastern Alberta assigns not only the Beaverhill Lake Formation but also the lower part of the Woodbend Group

to the Middle Devonian. On the other hand, Mound's (1966) conodont studies led him to conclude an Upper Devonian age for the Beaverhill Lake. To the west, the Flume has been placed in the Upper Devonian by most workers (see Mountjoy, 1965); although recently, Clark and Ethington (1965) from conodont studies, have placed all the Flume, except for a few feet at the top, in the Middle Devonian.

It is apparent that the exact position of the Middle-Upper Devonian boundary in western Canada is far from being settled. The fauna identified in the present study is very similar to the described Waterways fauna. It has, however, both Middle and Upper Devonian elements and the research required for an exact age assignment is far beyond the scope of the study. From an evaluation of previous studies, the Beaverhill Lake Group is tentatively considered in this study to be very early Upper Devonian.

Stratigraphic Grouping and Lithology

As mentioned earlier, Murray (1964) proposed that the Swan Hills Member be raised in status to Swan Hills Formation and the term Beaverhill Lake Formation be dropped in the Swan Hills area in favour of Waterways Formation. The writer agrees to giving formational status to the Swan Hills Member, but suggests group status for the Beaverhill Lake Formation rather than dropping the term. In this way, Waterways Formation can be used for the argillaceous basinal facies (as proposed by Murray) whereas the well-established term Beaverhill Lake can be used for the overall assemblage of platform, reef-complex,and basinal rocks in this area. The explanded knowledge of the units of distinct lithology in the Swan Hills area makes the group

status desirable. The economic importance, mappable character, wide areal extent, and thickness all justify the raising of the Swan Hills Member to formation status. Figure 3 gives the status and relationship of the units in the Swan Hills area as suggested in this paper. It is suggested that this terminology be adopted for the entire area of west-central Alberta that shows a recognizable development of the reef platform and associated reef complexes within the Beaverhill Lake strata. In the study area, the Beaverhill Lake Group is underlain by a detrital unit assigned here to the Watt Mountain Formation of the Elk Point Group, and is overlain by shales of the Woodbend Group (Figure 4). The upper contact, though gradational, is generally agreed upon by most workers. The lower contact, or base of the Beaverhill Lake Group, however, has been the subject of considerable controversy (see Figure 3).

The Fort Vermilion Formation, here considered the basal unit of the Beaverhill Lake Group, is only about five feet thick in the Carson Creek North area. Whether this unit should be included in the Beaverhill Lake or the Elk Point Group is debatable. Because of its thinness and the fact that it cannot be distinguished from the overlying reef-platform carbonates on electrical logs, it is here included within the Beaverhill Lake Group. Genetically, however, this unit is believed to belong more with the predominantly evaporite-clastic sedimentation of the underlying Elk Point deposits. For the purpose of the cross sections and maps the thin Fort Vermilion Formation is included in the Swan Hills Formation.

Underlying the Fort Vermilion Formation, the Watt Mountain Formation consists of a shale unit that in turn overlies a thin sandstone unit called the Gilwood Sand. Again there is a problem of where to put the approximately 50 feet of anhydrite

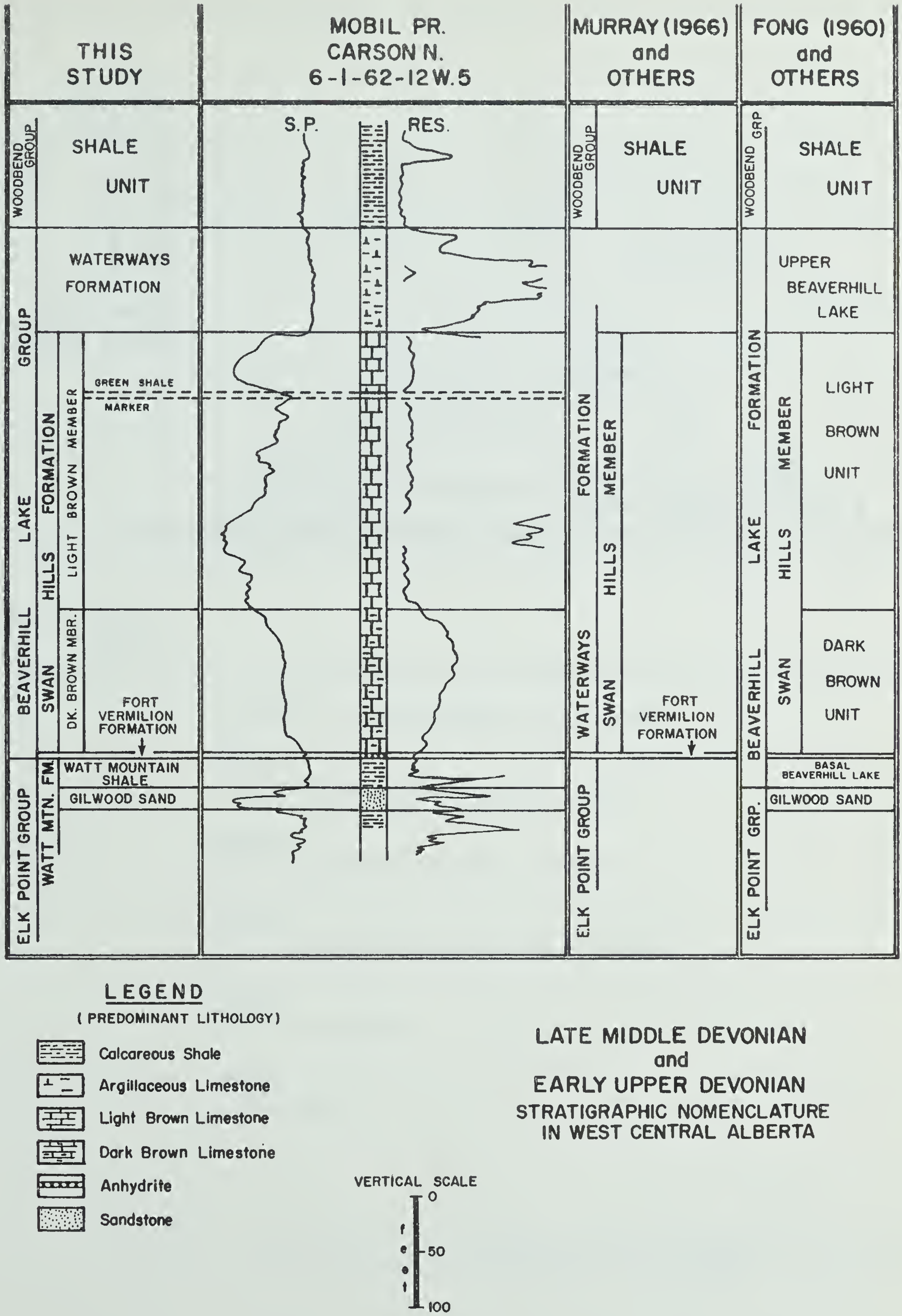
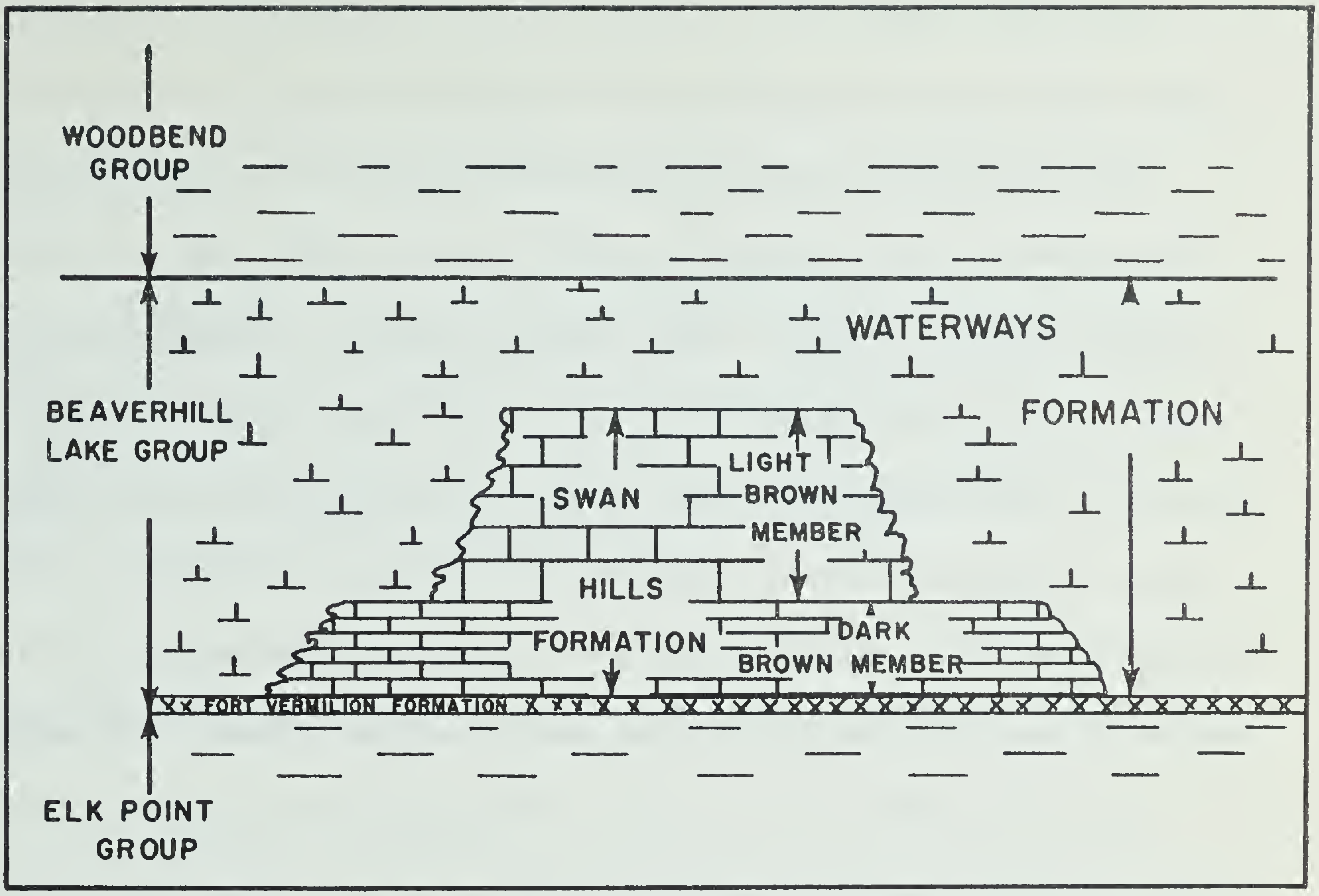


Figure 3. Late Middle Devonian and Early Upper Devonian Stratigraphic Nomenclature in West-Central Alberta



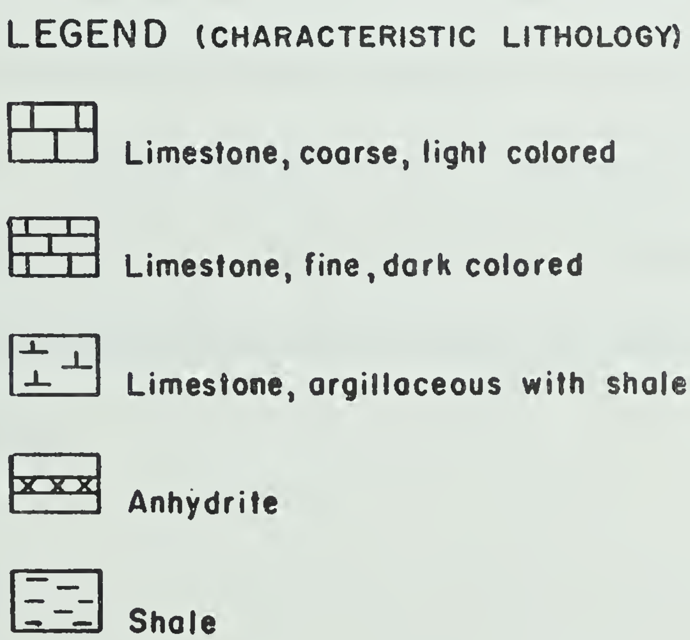


Figure 4. Stratigraphic Relationships of the Devonian Units Associated with the Carson Creek North Reef Complex

and shale that occurs between the Gilwood Sand and the lowermost Beaverhill Lake limestone. Fong (1960) called 43 feet of bedded anhydrite and shale his basal Beaverhill Lake unit and placed the boundary at the top of the Gilwood Sand (Figure 3). Edie (1961), and Jenik (1965), among others, have followed Fong's boundary designation. Thomas and Rhodes (1961), and Murray (1964), placed the base of the Beaverhill Lake Group at the top of the bedded anhydrite unit. Murray (1964) points out that the distinct lithology, easily recognizable nature, wide areal extent, and lithologic correlation with other areas, warrants the separation of this unit from the Beaverhill Lake Group. Fong (1960), and others, have stated that the sedimentation phase of the Gilwood Sand and overlying shale and anhydrite are more closely related to that of the Beaverhill Lake than to the underlying Elk Point. It is the writer's opinion that the anhydrite and the detrital nature of this unit is indicative of shallow water and restricted environments accompanying a regression or a standstill of the sea. It is thus thought to be a waning phase of the evaporitic sedimentation of the Upper Elk Point rather than an initial phase of the more normal marine transgression that deposited the thick carbonate-shale sequence of the Beaverhill Lake Group.

Elk Point Group:

Watt Mountain Formation

In the Swan Hills area the Gilwood Sandstone is about 25 feet thick, quartzose, and contains minor shale interbeds. It is brownish white in color, medium to coarse grained, moderately sorted, and slightly calcareous. The subangular to subrounded grains are predominantly quartz, but feldspar and rock fragments are present in

minor amounts. The porosity varies from about 6 per cent to 20 per cent with some oil staining. The argillaceous interbeds consist of waxy, blocky, dark grey to green shale.

Above the Gilwood Sand the Watt Mountain Formation consists of about 30 feet of shale with minor interbeds of anhydrite and limestone. This shale tends to be dark grey to black, blocky, hard, and slightly calcareous. The Watt Mountain can easily be recognized on electrical logs (Figure 3).

Beaverhill Lake Group:

Fort Vermilion Formation

This unit consists of bedded anhydrite with minor shale and dolomitic interbeds and is about 5 feet thick in the study area. The contact with the underlying Watt Mountain is gradational and is placed at the change in lithology from predominantly anhydrite to predominantly shale (Murray, 1965). The anhydrite consists of alternating light to dark brown layers, the color change, according to Murray (1965), being caused by the presence of varying amounts of organic matter. The shale interbeds are black to dark grey in color, fissile, dolomitic, and rich in organic matter.

Swan Hills Formation

Dark Brown Member - In the Carson Creek North area, the Fort Vermilion Formation is overlain everywhere by the reef platform or Dark Brown Member of the Swan Hills Formation. This platform is dominantly a dark brown, dense, slightly argillaceous limestone containing abundant *Amphipora*. In addition to *Amphipora* there

are also thin zones characterized by an abundance of other fossils such as the "Coral bed" (Fong, 1960), "Euryamphipora zone" (Jenik, 1965) as well as other thin zones with an abundance of cabbage-type stromatoporoids or brachiopods. Though the dark color is characteristic, some intervals or beds are light brown in color and are occasionally porous. The rocks of the platform often have a bedded appearance due to the parallel alignment of Amphipora stems and thin, dark, argillaceous or organic stringers. The thickness of the platform in the area averages about 120 feet.

Light Brown Member - The Light Brown Member, or reef complex, reaches a maximum thickness of about 340 feet. It can be divided into two major lithologic types:-

(1) Dense, pelletoidal, micritic limestones with abundant Amphipora.

(2) Porous, skeletal, coarse-grained limestones with abundant stromatoporoids, algae, and corals.

The first limestone type is very similar to that found in the reef platform. The rocks generally are very light to medium yellowish brown in color, and are characteristic of the central or interior portion of the reef complex. Bedding is commonly apparent. Amphipora and calcispheres tend to be the major skeletal constituents with abundant pellets, intraclasts, and micrite. Porosity varies but it is generally poor.

Limestones of the second type tend to form on the flanks of the above described amphiporoid limestones. They are characterized by an abundance of massive and tabular stromatoporoids, algae, corals, brachiopods, and crinoids, many of which are in growth position. These rocks tend to be porous, unbedded, coarse-grained, skeletal, and light colored except on the extreme outer flanks, where they become

finer grained, darker in color, and more dense.

In addition to the major types of limestone there are also found within the reef complex thin layers or beds of light green shale. These horizons are believed to represent breaks in the normal sedimentation, and periods of erosion and solution.

Waterways Formation

The off-reef or basinal facies of the Beaverhill Lake Group corresponds to the "Upper Beaverhill Lake" unit of Fong (1960), the Waterways Formation of Murray (1964), and the "Virginia Hills" member of Jenik (1965). It is composed essentially of a succession of dark grey to brown calcareous shales and argillaceous limestones. Nodular or "boudinage", thinly laminated, and massive limestones and shales are common rock types. Immediately above and adjacent to the reef complex, the basinal facies tends to become more calcareous and fossiliferous. This is exemplified in the so-called "reef rubble zone" (Jenik, 1965). The maximum thickness of the basinal facies in the area studied is about 375 feet. Regionally, however, this unit varies in thickness from zero to over 700 feet. It is absent where there is continuous reefal development from the Swan Hills up into the Woodbend, such as in the Windfall area, and reaches its maximum thickness where the Swan Hills Formation is absent (Geological History of Western Canada. 1964). For a thorough description and interpretation of this off-reef or basinal facies the reader is referred to Murray (1965).

Woodbend Group:

The Beaverhill Lake Group in the Swan Hills area is overlain by shales and argillaceous limestones of the Woodbend Group. This shale sequence is equivalent to the Cooking Lake and Duvernay Formations to the southeast (Fong, 1960). Fong termed this argillaceous sequence the "shale unit" in the Swan Hills area, and this terminology has been carried on by most subsequent workers.

Geological History

Near the end of Middle Devonian time there was a general uplift of a large part of the Western Canada Sedimentary Basin. This uplift was accompanied by a regression of the sea marked in some areas, especially to the north, by an erosional unconformity (Warren and Stelck, 1950) and in others by clastic and evaporite deposition. In the Swan Hills area, the Gilwood Sand, Watt Mountain shales, and Fort Vermilion evaporites are believed to represent the waning stages of this period of uplift. This period of regression and stillstand was followed by a long period of transgression that resulted in the deposition of the thick Upper Devonian series of rocks. Within this general period of transgression there were, however, minor regressive oscillations marked by uplift and erosion.

The first incursion of normal marine waters resulted in the deposition of a basal limestone unit throughout most of Alberta. The rate of subsidence is believed to have been moderate since the Slave Point and equivalent rocks in Alberta are not of a deep-water character. In northeastern British Columbia, a reef complex formed along the edge of the basal carbonate platform (Gray and Kassube, 1963). The reef barrier

separated deep-water argillaceous deposition to the north from shallow-water shelf deposition to the south.

Following the mild initial transgression there was a more extensive transgressive phase that resulted in the deposition of the Beaverhill Lake sediments. At this time, the reef complexes and the carbonate shelf front shifted much farther to the south into central Alberta. Due to the greater rate of subsidence, the biohermal Swan Hills reef complexes extended vertically instead of laterally like the underlying biostromal reef platform. The reef-covered platform edge, now situated in central Alberta, again separated the deep-water basins to the north from the shallow-water shelves to the south. Though nowhere in any of the core studied was there any evidence of a major break or unconformity, brief periods of uplift and regression are marked within this Beaverhill Lake transgressive phase by thin green shale beds, reef rubble zones, and pyritized erosional surfaces.

Following Beaverhill Lake time there was another period of very mild transgression or stillstand. This resulted in the deposition of the Cooking Lake platform or shelf limestones. This time interval in turn was followed by the last major transgression of the Devonian that developed the biohermal Leduc reefs.

In summary, Beaverhill Lake deposits represent one major phase in the overall Devonian transgression towards the shield from deep water to the northwest. These major transgressive periods were separated by intervals of stillstand or mild transgression resulting in the development of shelf or platform carbonates. The platform edge tended to move southward or shelfward with each ensuing transgressive phase and was marked

by biohermal reef complexes. At the same time, localized and isolated reefs tended to form in the basin in front of the barrier. A diagramatic sketch of the approximate carbonate front positions during different stages of late Middle and early Upper Devonian time is shown in Figure 2. The Peace River Arch and probably much of the Western Alberta Ridge was above sea level during Beaverhill Lake time. These features are believed to have been very important and perhaps the key to the Beaverhill Lake and the later Woodbend reef complex - shale basin configurations and associations. The exact character of the Canadian Shield area during Beaverhill Lake time is obscured because of extensive pre-Cretaceous erosion in this region.

CHAPTER 3 - STRUCTURE AND GEOMETRY OF THE SWAN HILLS FORMATION

Reef Platform (Dark Brown Member)

Size and Form:

The reef platform is an extensive, carbonate bank present throughout the study area. Murray (1966) shows the approximate extent of this unit in the Swan Hills region, and places its depositional edge about six miles east of the Carson Creek North reef complex.

An isopach map of the platform was not constructed because only a few of the wells in the area penetrated its base. Cross sections shown in Figure 5, however, indicate that its thickness does not change significantly save for a moderate thickening to the west and southwest. In the wells studied the thickness ranges from about 100 to 160 feet with the average being around 120 feet.

Jenik (1965) suggests that in the Goose River field the thickest areas of the platform were the sites on which the younger reef complexes developed. This appears to have been the case in the Carson Creek area as well, but lack of sufficient deep well control prevents confirmation.

Paleotopography:

The regional dip and strike of the Beaverhill Lake strata in the Carson Creek area were calculated by constructing a structure contour map on the base of the Swan

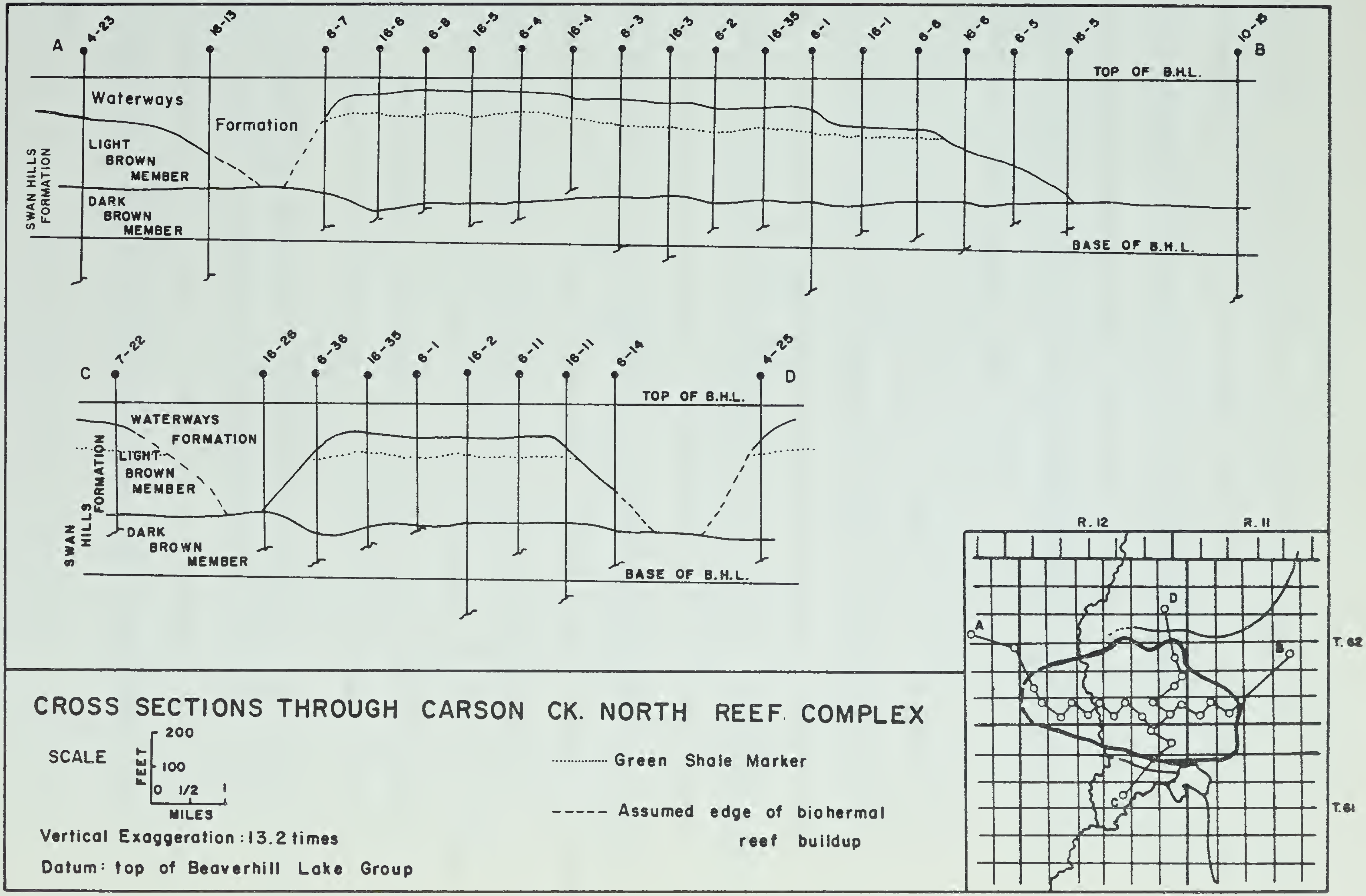


Figure 5. Cross Sections through Carson Creek North Reef Complex

Hills Formation. From the available data, the present day regional dip is approximately 40 feet per mile in a south fifty-five degree west direction. This structure was removed by rotating the beds about a datum line drawn parallel to the regional strike. The corrected sub-sealevel depths of the units after rotation are given in Appendix 1. As pointed out by KJovan (1963), removing the regional dip gives a much closer approximation to the original topography before tilting.

An interpretation of the gross topographic features of the reef platform just prior to initiation of reef growth is presented in Figure 6. Though well control is sufficient, the gradational contact between the platform and the overlying reef complex makes an exact placing of the boundary not always possible. From Figure 6 the general trend of the platform appears to have been in a north to northeast direction, but there are many prominent irregularities in this trend with the presence of highs running perpendicular to it. One such structurally high lobe appears to underlie the Carson Creek North reef complex. These highs tend to be separated by narrow lows or channels (?) that more or less underlie the prominent channels between the overlying biohermal reef complexes. It thus appears that the loci of the Swan Hills biohermal reef complexes were controlled in part by the topography of the underlying reef platform. Whether these high areas on the reef platform surface were caused by pre-existing tectonic features or are due to thicker sediment sections is not known. It is also possible that the irregularities on the reef platform surface are only apparent because of correlation difficulties or post-Devonian folding (Edie, 1966, personal communication).

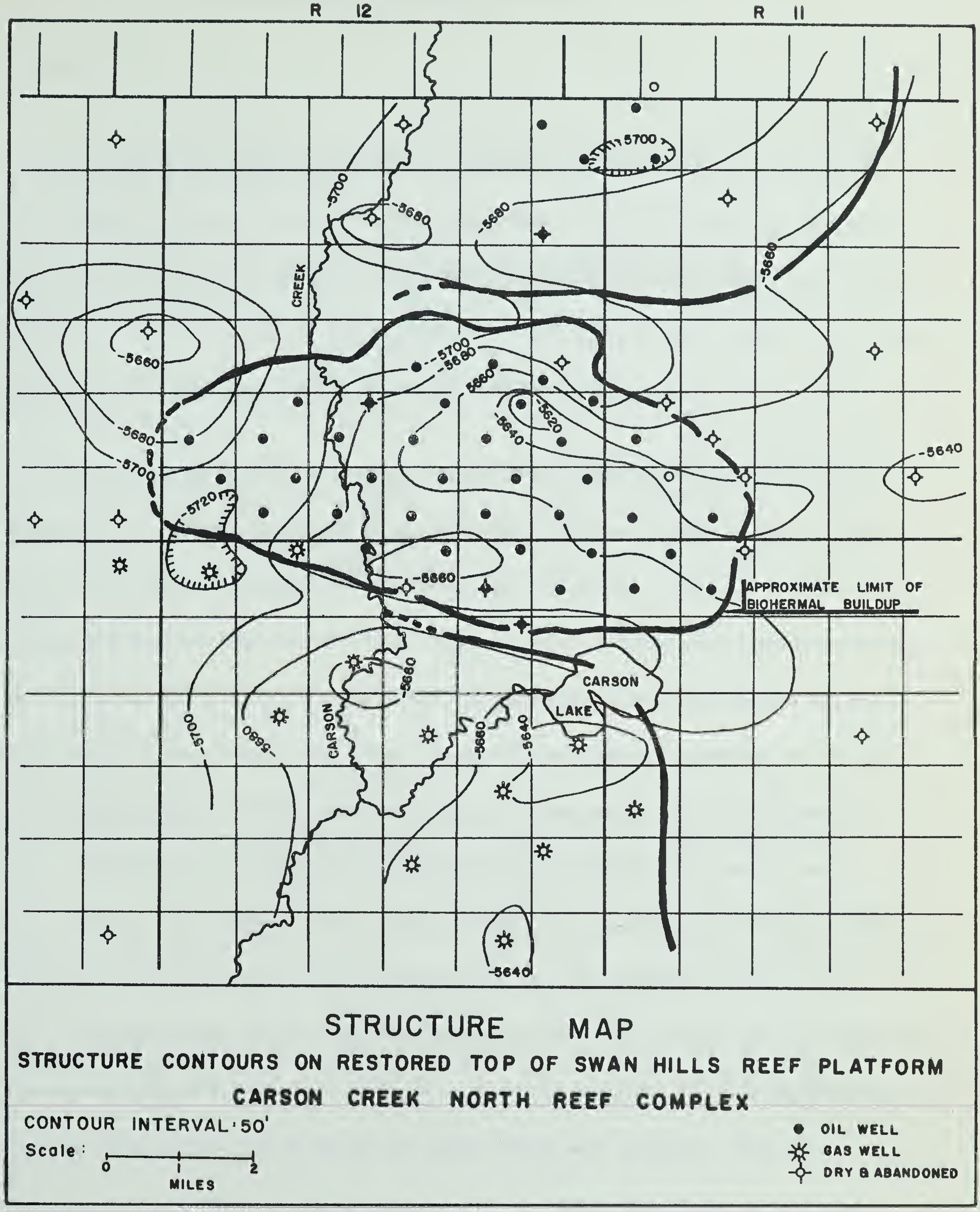


Figure 6. Structure Contour Map of the Swan Hills Reef Platform, Carson Creek North Reef Complex, after Removal of the Regional Dip

Reef Complex (Light Brown Member)

Size and Form:

The approximate shape and extent of the Carson Creek North reef complex is given in Figure 7. Because of the wide well-spacing in the field (two wells per square mile), a contour interval of 50 feet was found to best show the shape clearly and include the important features found. The character and extent of the western edge of the complex is not known because of the lack of well control in that area.

The reef complex is an elliptically shaped mass, approximately 8 miles long by 3 miles wide, and covers an area of 24 square miles at its base. Deep narrow channels separate it from similar buildups to the north, west, and south. To date, no similar buildup to the east has been found. These channels were probably very important during Swan Hills time, allowing circulation of well oxygenated and nutrient-loaded marine water throughout the platform area. The slopes of the complex are steepest on the southern and western sides, while the seaward slopes on the eastern flank are considerably gentler. The crest and thickest section of the complex is found in the western part. Previous workers such as Edie (1961), Klovan (1964), Jenik (1965), and Murray (1966) have found this to be the case in many other Devonian reef complexes as well. To Klovan, this suggests that the actual growing organic-reef, did not grow up into the zone of vigorous wave action because it does not form the present crest. This interpretation may not be valid in the case of the Carson Creek North reef complex. Here, the present day crest and thickest section may not be the same as that during active reef growth. There is evidence for considerable erosion within and at the top of the complex (especially on the eastern side). In addition, the possibility of differential compaction

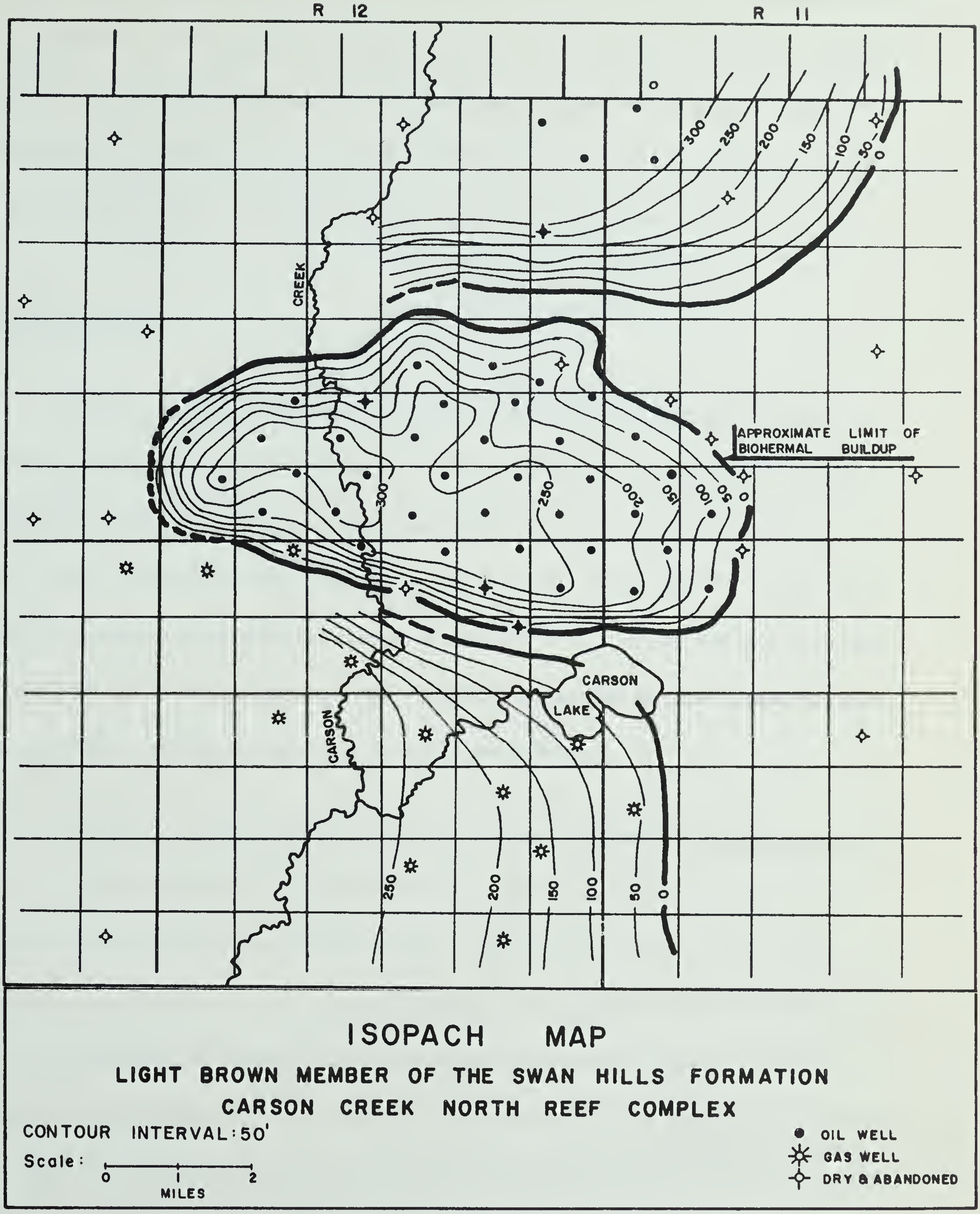


Figure 7. Isopach Map of the Light Brown Member of the Swan Hills Formation, Carson Creek North Reef Complex

and the covering of the complex by a thick bioclastic unit would tend to change the original topographic surface below the green shale marker. The lack of any good time horizons makes the task of reconstructing a typical reef-complex profile almost impossible. The present upper surface of the complex and the extensive green shale marker, which are in the writer's opinion largely erosional surfaces cannot be used for this purpose.

Paleotopography:

The structure map and cross sections (Figures 8 and 5) illustrate the general morphological features on the reef complex. Figure 8 shows a relatively flat, plateau-like surface on top of the eastern half of the reef that rises to an elevated crest on the western side. The cross section in Figure 5 also shows this flat-topped nature and indicates, the presence of possible terraces on the eastern side. Similar features have been reported from other reef complexes. Murray (1966) states that terraces appear to have been significant throughout the whole Swan Hills archipelago.

As pointed out earlier, the steepest flanks of the complex, averaging about five degrees, occur along the southern side. The more gentle slopes on the eastern flank have only about one and one-half degree dip. The presence of two or three major channels or re-entrants cutting across the complex are suggested by the maps of Figures 7 and 8. These may have been similar to channels that are found cutting across the reef front in most modern reefs. The lack of close control and the presence of a calcarenite blanket covering the complex prevents the recognition of most of these topographic features. It is not known whether these channels and the previously mentioned terraces represent submarine erosion by current and wave action or subaerial erosion. It is possible that both agencies played a role in the formation of these interesting features.

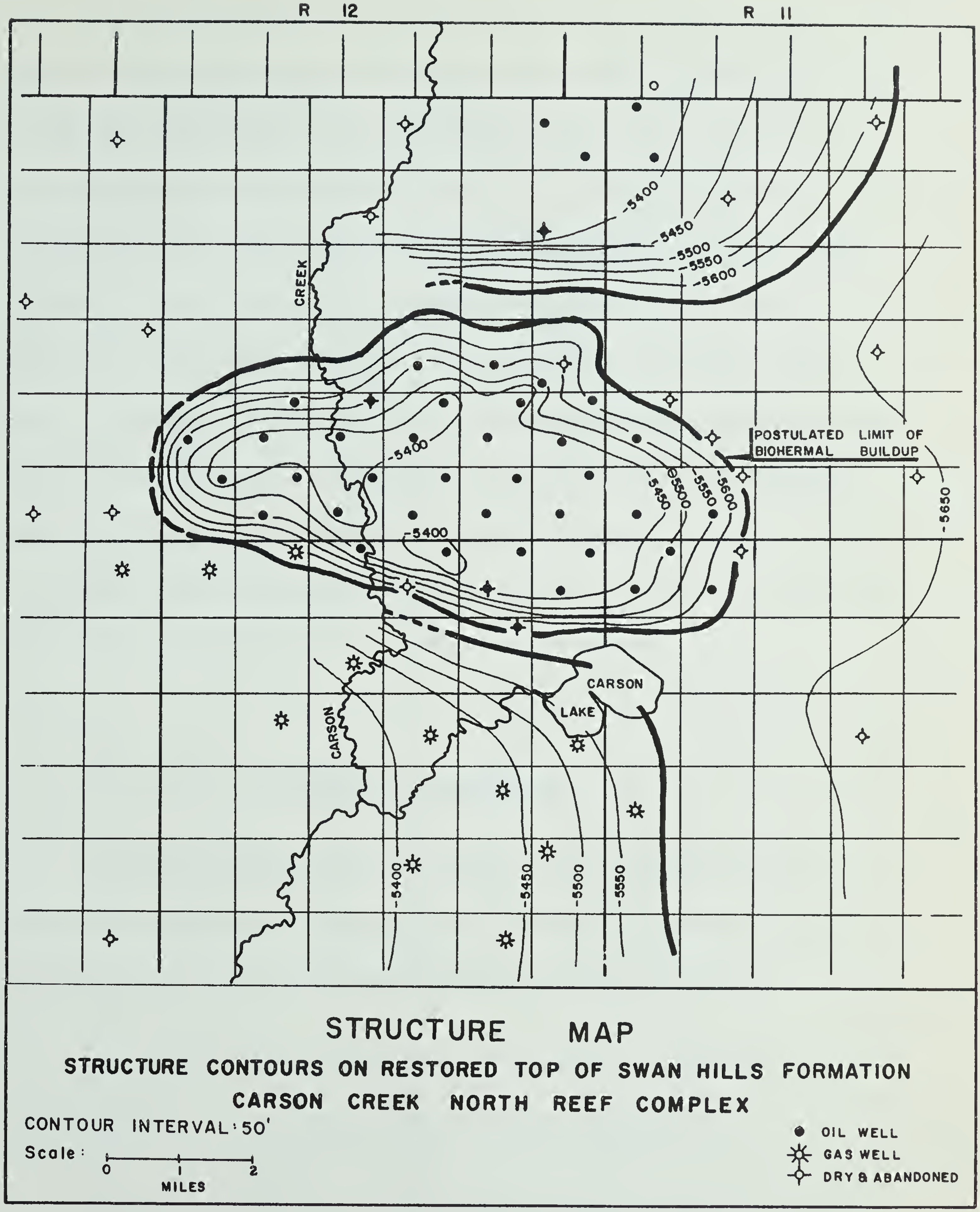


Figure 8. Structure Contour Map of the top of the Swan Hills Formation, Carson Creek North Reef Complex, after Removal of the Regional Dip

The lateral persistence of the green shale marker throughout the Carson Creek North and adjacent reef complexes is well illustrated in Figure 5. This unit, though possibly most evident in the Carson Creek North area, occurs in most of the Swan Hills reef complexes described in the literature. It is believed to represent a period of uplift and erosion during which time Carson Creek North along with the other buildups in the Swan Hills area were leveled-off or peneplaned to a height now marked by the green shale microfacies. After this important break there does not appear to have been any major reef complex formed at Carson Creek North. Rather, the rest of Swan Hills time is represented by a relatively homogenous, fragmental, calcarenite unit containing abundant stromatoporoid fragments. This unit is believed to represent a normal, shallow-water bank or shelf deposit rather than a reef complex with its lateral zonation of fore-reef, reef and back-reef areas.

Electrical Log Interpretation

The east-west cross section of Figure 9 shows the character of the units in question on the Spontaneous Potential (S.P.) and Resistivity electrical logs. The characteristics of the units on the logs as used in this study are as follows:

The top of the Beaverhill Lake Group is picked on the Resistivity-Log at the sharp deflection to the right indicating an increase in the resistivity.

The upper contact of the Swan Hills reef complex is marked by a deflection to the left or marked increase in negativity on the S.P. Curve and an increase in resistivity.

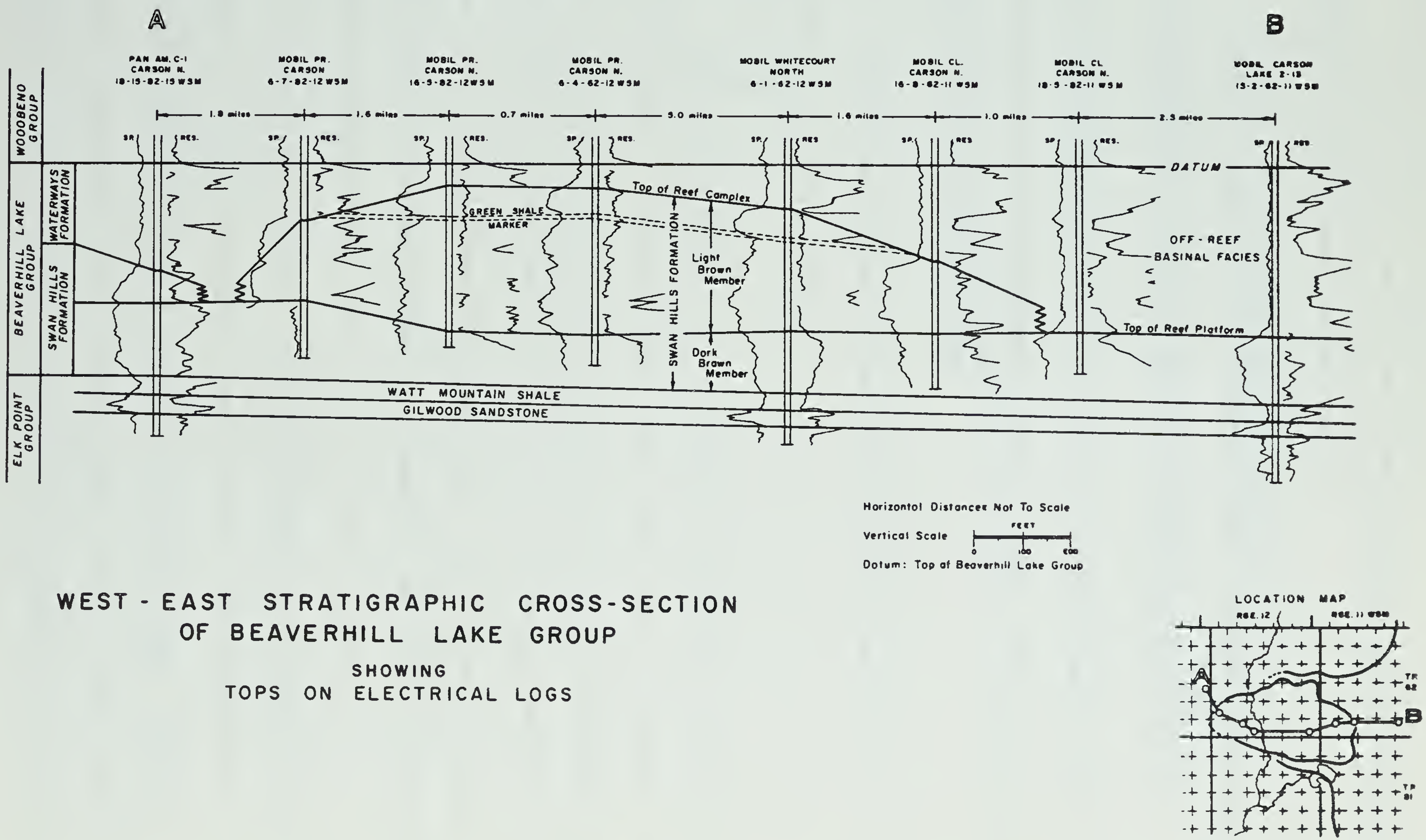


Figure 9. West – East Stratigraphic Cross Section showing Tops on Electrical Logs (Carson Creek North Reef Complex)

The reef platform usually shows a marked increase in resistivity and a more positive S.P. than the overlying reef complex.

The thin, anhydritic Fort Vermilion Formation at Carson Creek North usually cannot be picked on the electric logs and is included in the reef platform.

The top of the Watt Mountain Formation is characterized by a sharp decrease in resistivity and a positive deflection of the S.P. curve. This unit can also be readily picked on the gamma ray log.

The Gilwood Sand unit can be picked from within the Watt Mountain Shale by its more positive S.P. reading.

There is little change in total thickness of the Beaverhill Lake Group in going from reef to off-reef areas, as is evident from Figure 9. The gradual thinning of the unit by about 45 to 50 feet in going from B to A on the cross section fits the regional thinning of the Beaverhill Lake Group in a westward direction, and has little to do with the presence of the reef buildup. Also, little or no draping of the younger beds over the reef complex can be detected. By the time the shale and argillaceous limestone sedimentation occurred over the top of the complex there may have been little difference in elevation between the reef complex and off-reef sediments. This does not necessarily mean, however, that the sedimentation in the basin always kept pace with the growth of the reef complex. The lack of traceable time markers in logs or lithology makes correlation between reef and off-reef sections difficult at present. Thus one can only speculate as to the relative

sedimentation rates of the two different facies.

Summary and Interpretation

The Carson Creek North reef complex may have formed on a pre-existing high on the underlying reef platform.

The geometry and paleotopography of the top of the reef complex found preserved in the geological record may not correspond to a typical profile present during a period of normal reef development in Swan Hills time. This is because the green shale marker and the reef complex top are considered here to be largely erosional rather than depositional features (for further discussion on these erosional features see Chapters 6 and 9).

Correlation between reef and off-reef areas is difficult, but it is the writer's opinion that during deposition of the approximately 200 feet of Swan Hills strata between the reef platform and the green shale marker, there was considerable relief between the reef complex and the off-reef or basinal sediments. The reasons for this belief are as follows:

(1) There are few or no clay minerals or argillaceous matter in most of the reef-complex sediments.

(2) There is a very sharp boundary between reef complex and basinal sediments, and in all wells studies no interfingering of the two facies was found.

(3) The distinctly different lithologies and textures of the two facies indicates vastly different environmental conditions.

(4) A certain amount of _in situ_ organic reef has been identified.

(5) A large amount of coarse reef detritus is found on the fore-reef slopes.

(6) The fossils found in the two facies indicates a variation in habitat from shallow to relatively deeper water.

It is further postulated here that during the time the rocks between the base of the green shale marker and the top of the reef complex were deposited, the major portion of the 300 feet of off-reef shales and limestones was deposited. If the green shale indicates uplift and erosion, then there was probably an influx of sediment being deposited in the shallow off-reef basins at this time. Thus, during this time the basins were probably being rapidly filled while the reef complexes were undergoing erosion and the removal of perhaps 50 to 100 feet of relief. There is no evidence known to the writer that the off-reef basinal areas were subaerially exposed at this time. With the following submergence of the reef complexes there was probably only minor relief between the reefs and basins. Thus, the remaining Swan Hills sedimentation at the Carson Creek North field consisted of a wide-spread, skeletal calcarenite which is a typical shallow-water bank type of deposit. Finally, another period of erosion and possible uplift is evident from the character of the top of the reef complex (Plate XX, Figure 1). This phase probably completely wiped out any relief of the reef complex and the ensuing deepening of the water resulted in muddy, basinal sediments being deposited over the reef complexes as well as in the off-reef areas.

Considering the paleogeographic setting of the Carson Creek North reef complex,

the available evidence indicates that the deep marine Beaverhill Lake sea was to the east. The shape of the complex and deep channels, the prolific reef growth on the east side, and the lateral zonation suggest that the prevailing wind and wave direction was from the east. The location and initial growth of the Swan Hills reef complexes is believed to have been largely controlled by the nature of the underlying platform and by the presence of nearby land masses. The later development, shape, and extent of the reefs was probably controlled largely by other physical agencies, namely; climate, water depth, wind, waves, currents, and chemistry of the water.

CHAPTER 4 - PETROGRAPHY

Techniques

As stated earlier, a pilot study on core from the Redwater reef complex was made by the writer in the summer of 1964. This brief project was primarily a petrographic study of the various rock types and facies. Following this, a similar reconnaissance petrographic study on all the available Carson Creek North core was carried out. These initial studies outlined the lithological variations that could be expected and enabled the writer to choose the most useful classification and textural parameters for the final petrographic analysis. The study also emphasized the fact that in order to fully appreciate the total aspect of reef petrology an integrated use of hand specimen, stereo-microscope, and thin section study is required.

For the most part, the petrographic study consisted of a detailed examination of slabbed core under the stereo-microscope. The slabs were first covered with mineral oil to bring out the textural details, and many were polished to remove saw marks or etched to remove carbonate dust coatings. During this study, the type, size, and abundance of the various textural components were entered on data sheets like the one shown in Table 2.

In addition to the stereo-microscope examination, more than 300 acetate peels and thin sections were examined under the petrographic microscope. A few important uses of acetate peels in reef complex studies are as follows. Peels of the various lithologies can be made for quick references and for permanent records; they can be

Table 2 - Reef Complex Data Sheet

REEF COMPLEX DESCRIPTION SHEET

WELL:

SHEET NUMBER

SAMPLE No.																									
[1] % Framework >2 mm.																									
[1] % Lithoclasts																									
[1] % Skeletal																									
[2] Massive Stroms																									
[2] Tabular Stroms																									
[2] Idio Stroms																									
[2] Corals																									
[2] Algae																									
[2] Brachiopods																									
[2] Pelecypods																									
[2] Oncolites																									
[2] Biolithite																									
[1] % Grains 2-.03mm.																									
[2] Skeletal																									
[2] Pellets																									
[2] Intraclasts																									
[2] Coated Grains																									
[2] Calcispheres																									
[3] Average Grain Size																									
[1] Groundmass – Infill																									
[1] Lime Mud - Micrite																									
[1] Spar : Calcite																									
[1] : Dolomite																									
[2] Shaly - Argillaceous																									
[2] Chert - Quartz																									
[2] Pyrite																									
[2] Gypsum - Anhydrite																									
[2] Fractures																									
[2] Stylolites																									
[2] Dried Hydrocarbon																									
[4] General Appearance or Fabric																									
[5] Color																									
[6] Roundness																									
[7] Sorting																									
[8] Packing																									
[9,10] Porosity																									
Grain/Groundmass Ratio																									
[11] Fossil Content																									
[11] Stromatoporoids: Massive																									
[11] " : Tabular																									
[11] " : Stachyodes																									
[11] " : Amphipora																									
[11] " : Bulbous																									
[11] Corals : Tabulate																									
[11] : Rugose Cup																									
[11] Brachiopods : Whole																									
[11] " : Broken																									
[11] Algae : Solenoporaceae																									
[11] " : Coated																									
[11] " : Mat																									
[11] Pelecypods																									
[11] Gastropods																									
[11] Ostracods																									
[11] Crinoids - Bryozoa																									
[11] Calcispheres – Others																									
[12] Environment																									
[13] Classification																									
ROCK TYPE																									

made of areas that appear to have interesting features and often illustrate where thin sections are needed; they can be used for stromatoporoid, coral, and bryozoan identifications; and finally, they can be used as negatives for photography. Plexiglass peels (Frank, 1965) were also made but were not as useful as the acetate peels.

Thin sections were made where detailed textural and diagenetic features were not recognizable under the stereo-microscope. Thin sections were also made of all the principal rock types, and more than 50 thin sections of stromatoporoid specimens were studied for identification purposes.

Alizarin Red S stain (Friedman, 1959), was used on some thin sections and polished sections to differentiate between dolomite and calcite and to better bring out textural details in the dolomitized areas.

Classification

One of the first problems that must be overcome in a study such as the present one is the choice of a petrographic classification to be followed. The classification used here (Table 3) is the result of combining, with some modifications, features of both Folk's (1959) and Leighton and Pendexter's (1962) classifications. As pointed out by Murray (1966, p. 29) the majority of the existing limestone classifications are designed primarily for shelf carbonates rather than reef complexes with their multiple textural and compositional variations.

The measurable factors on which the classification is based are the size, abundance, and the type of carbonate particles, and the relative abundance of micrite.

Table 3. - Classification for Reef-Complex Limestones

<table>
<tr><th rowspan="2">MODIFIERS</th><th rowspan="2">FRAMEWORK PLUS GRAINS : MICRITE RATIO</th><th colspan="5">CONSTITUENT GRAINS</th><th rowspan="2">ORGANIC-REEF DEPOSITS</th></tr>
<tr><th>PELLETS</th><th>PELLETS and INTRACLASTS</th><th>INTRACLASTS</th><th>COATED GRAINS</th><th>SKELETAL GRAINS</th></tr>
<tr><td rowspan="4">(1) <u>FRAMEWORK ORGANISMS</u> (<u>Amphipora</u> pelsparite etc.)

(2) <u>COLOR</u> (Dark brown pelsparite etc.)

(3) <u>TEXTURE</u> (laminated pelsparite etc.)

(4) <u>CEMENT</u> (sparry pelmicrite etc.)

(5) POROSITY (porous pelsparite etc.)

(6) <u>IMPURITIES</u> (argillaceous pelsparite etc.)</td><td>9:1</td><td>PELLET limestone calcirudite etc.</td><td>INTRAPEL limestone, calcirudite etc.</td><td>INTRACLAST limestone, calcirudite etc.</td><td>OÖLITE, PISOLITE, ALGAL COATED limestone, calcirudite etc.</td><td>SKELETAL limestone, calcirudite, etc.</td><td rowspan="4">(a) <u>BIOLITHITE</u> (<u>In situ</u> organic framework)

(b) REEFOID LIMESTONE (Coarse skeletal limestone with reef organisms essentially in place or having undergone only minor transport)</td></tr>
<tr><td>SPAR greater than MICRITE</td><td>PELSPARITE</td><td>INTRA-PELSPARITE</td><td>INTRASPARITE</td><td>OÖSPARITE etc.</td><td>BIOSPARITE</td></tr>
<tr><td>MICRITE greater than SPAR
9:1</td><td>PELMICRITE</td><td>INTRA-PELMICRITE</td><td>INTRAMICRITE</td><td>OÖMICRITE etc.</td><td>BIOMICRITE</td></tr>
<tr><td></td><td colspan="5">MICRITIC LIMESTONE</td></tr>
</table>

energy usually increasing →

energy usually increasing ↑

The classification is of necessity descriptive, though genetic implications are emphasized where possible for the purpose of environmental reconstructions. The terminology and the use of the sparry calcite: micrite ratio largely follows Folk (1959). The arrangement of the chart, the textural components, and the grain: micrite ratio largely follows Leighton and Pendexter (1962). The use of the term "reefoid limestone" for nearly in situ reef derived debris and the modifiers used in naming the rock types are the writer's adaptations.

As shown in Table 3 the main rock names are set up to reflect increasing energy regimes going from bottom to top and to a certain extent in going from left to right on the chart. The upward vertical increase in energy corresponds to a relative decrease in micrite. The possible energy increase from left to right is reflected by the dominant grain type. It is emphasized, however, that this is only meant to be a generalization of the energy conditions and that many exceptions exist.

The six classes of modifiers (others may be added if desired) shown on the left side of Table 3 are primarily descriptive for portraying the various rock types. The features that are most characteristic of the physical appearance of the rocks are added adjectivally to the basic rock types. These modifying adjectives are important not only for descriptive purposes, but also have important environmental implications.

An example of the data sheets used during the petrographic study is shown in Table 2. This work sheet has been divided into five major groupings for the purpose of data recording. The major categories are framework, grains, groundmass and infill, general appearance or fabric, and fossil content. Within these major groups there are further subdivisions of components. From a quantitative and qualitative analysis

of the data recorded in these subdivisions, the final three columns at the right of the data sheet, namely, the environment of deposition, the genetic classification, and the rock name can be filled in. These data sheets are then used as log-information charts in the construction of reef cross sections and facies analysis maps.

Table 4 shows the legend or key used in filling out the data sheet. This table gives the symbols for a number of characteristics, both quantitative and qualitative, that are used in describing the various components of the data sheet.

Petrography of the Textural Components

The following defines and briefly describes the character of the more common textural components found within the rocks of the complex. The components are discussed under the main headings of the data sheets.

(1) Framework (Particles greater than 2mm):

The writer agrees with Klovan (1963, p. 40) in stressing that the presence or absence and the type of the coarse components are important criteria in classifying limestones and interpreting depositional environments. This is especially evident for reef and reef-detritus rocks. The framework constituents can be subdivided into 2 major categories: skeletal and non-skeletal (lithoclasts).

The lithoclasts or rock fragments are often important constituents locally, but in general are not very abundant. When found within rocks of the reef complex proper, the lithoclasts are usually very similar in composition to the enclosing carbonate sedim-

Table 4. - Key for Reef Complex Description Sheets

1. PERCENTAGE

2 = 20%
3-7 = 30% to 70%
etc.

2. AMOUNT

ab = abundant > 30%
c = common 10-30%
t = trace 0-10%
np = not present

3. AVERAGE GRAIN SIZE

vc = very coarse 1-2 mm.
c = coarse .5-1 mm.
m = medium .25-.5 mm.
f = fine .125-.25 mm.
vf = very fine .03-.125 mm

4. GENERAL APPEARANCE

M = massive
N = nodular
L = laminated
Br = brecciated
B = bored
V = vuggy
Mt = mottled
O = organic lattice
F = fragmental

5. COLOR

10 YR 4/2 = dark yellowish brown
etc.

6. ROUNDNESS

A = angular
Sa = subangular
Sr = subrounded
R = rounded

7. SORTING

p = poor = 5 or more grades
m = moderate = 3 or 4 grades
w = well = 1 or 2 grades

8. PACKING

Ic = grains in contact
Fl = grains floating

9. POROSITY TYPE

x = intergranular or intercrystalline
o = intraskeletal
v = vuggy
f = fracture

10. POROSITY GRADE

g = good > 20%
m = medium 12-20%
p = poor 6-12%
s = slight < 6%

11. FOSSIL CONTENT

X = abundant fossil constituent
V = rare fossil constituent

12. ENVIRONMENT

B = basin
FR = fore-reef
R = reef
BR = back-reef
L = lagoon
P = platform

13. CLASSIFICATION

Be = beach
Ch = channel
Dr = deep reducing
Ds = deep shoal
Ir = inter-reef
It = intertidal
Is = intermediate shoal
Rd = reef detritus
Ro = organic reef
Se = erosional surface
Sr = shallow reducing
Ss = shallow shoal
St = supratidal deposit
Tf = tidal flat

ments. (Plate I, Figure 1). This implies that the lithoclasts represent ripped-up parts of the partially consolidated sea floor that were deposited close by in more or less the same environment. This mixing process could result from strong wave or current action, from periodic storm activity, or from biologic activity. The lithoclasts are very similar in appearance, and probably in mode of formation, to the smaller intraclasts.

Lithoclasts also occur in the calcirudites and breccias where they usually occur in a matrix of slightly different composition. The limestone breccia associated with the green shale marker is a good example of this type of lithoclast occurrence (Plate I, Figure 2). This breccia, however, may be largely a solution breccia with little or no water transportation.

The third common occurrence of lithoclasts is in the off-reef argillaceous limestones and reef-rubble zones. Many of the Waterways limestones adjacent to the reef complex contain subangular to subrounded lighter-colored lithoclasts within the dark basinal sediments. Most of these fragments have formed from the deformation and plastic flow of thin limestone bands, (Plate I, Figure 3), but others appear to have been transported and deposited as such in the off-reef environment. These lithoclasts probably represent parts of the adjacent reef complex or shallow carbonate areas that were eroded during periodic storms and transported to the deeper, more quiet, off-reef environment. These lithoclasts are very similar in appearance to the limestones making up the reef-rubble zone (Plate I, Figure 4), that occur in some of the back-reef wells at the contact between the reef complex and the Waterways basinal facies. The reef-rubble zone contains both lithoclasts and fossil fragments in a micritic matrix.

PLATE I

Framework Constituents
(Hand specimens, with centimeter scale)

Figure 1. Lithoclasts. Abundant angular lithoclasts in a matrix of a similar micritic character. Note the stylolite at the top of the picture and the mottling (Location, 6-4-62-12, 8542').

Figure 2. Lithoclasts. Green shale - limestone breccia containing numerous lithoclasts and skeletal fragments. Note abundant sparry calcite (Location, 6-36-61-12, 8997').

Figure 3. Lithoclasts. Argillaceous nodular limestone believed due to compaction (Location, 16-26-61-12, 8680').

Figure 4. Lithoclasts. Reef-rubble zone. Note borings near base of picture (Location, 6-7-62-12, 8996').

Figure 5. Skeletal framework constituents. Largely tabular stromatoporoids with brachiopods, crinoids and solenoporoid algae common (Location, 16-6-62-11, 8792').

Figure 6. Skeletal framework constituents. Largely Stachyodes fragments. Note oncolite in upper right hand corner of photograph (Location, 6-36-61-12, 8652').

Figure 7. Oncolites. The oncolites tend to have stromatoporoid fragments as nuclei. Note the stylolitic contact of the massive stromatoporoid fragment to the right centre of the photograph (Location, 6-11-62-12, 8657').

Figure 8. Biolithite. Intergrown massive and tabular stromatoporoids enclosing pockets of coarse skeletal debris (Location, 6-1-62-12, 8780').

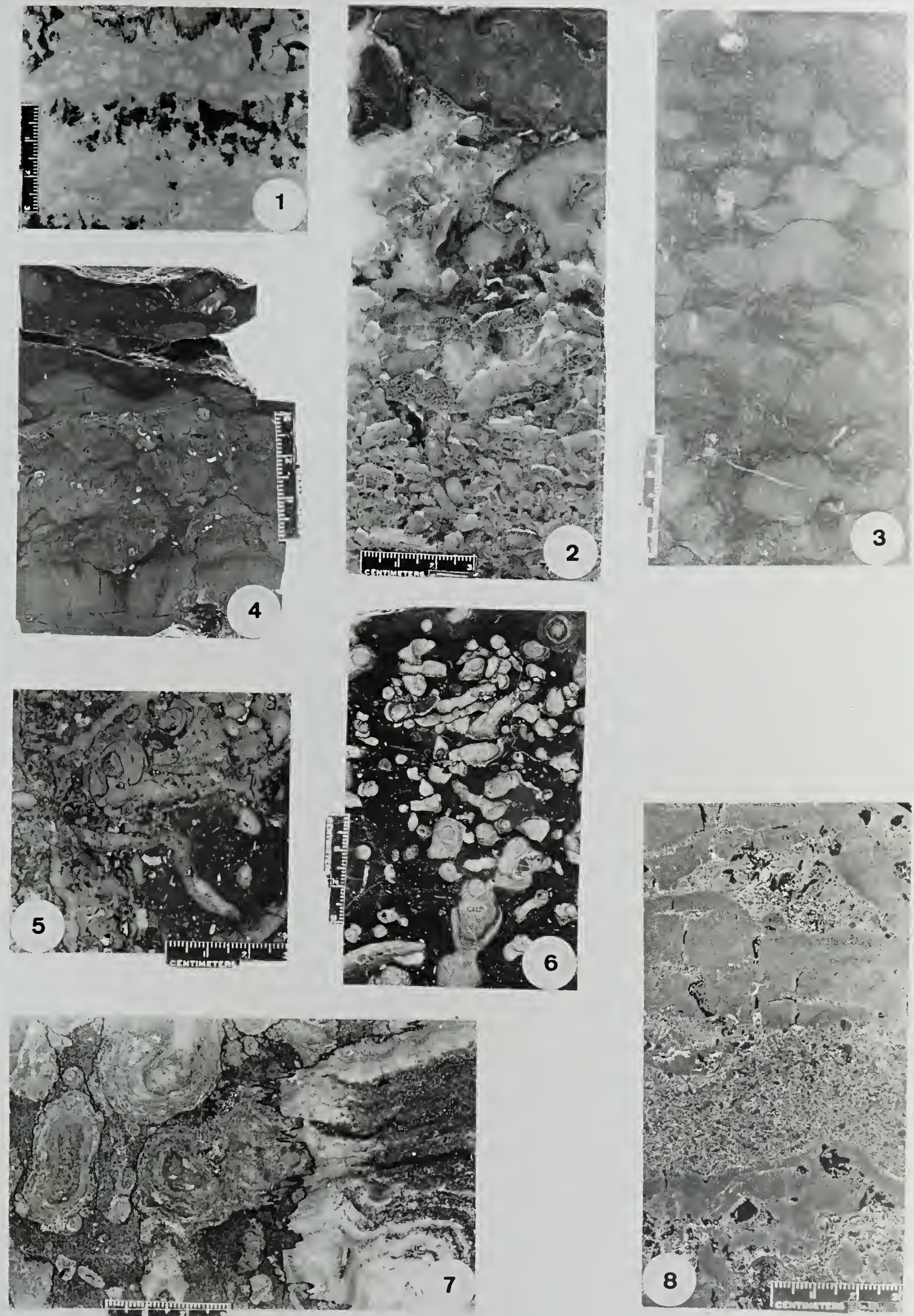


PLATE I.

The megascopic fossils or skeletal materials are by far the most abundant framework constituents in the reef complex (Plate 1, Figures 5 and 6). Stromatoporoids are the most plentiful and were the most important organism in the overall growth and evolution of the reef complex. Brachiopods, corals, solenoporoid algae, crinoids, and gastropods are other common framework organisms. Pelecypod, bryozoan, echinoderm, and other skeletal framework fragments have been found, but they are neither abundant nor important. The higher taxonomic categories can readily be identified from hand specimens of these framework fossils. The distinguishing characteristics of the various framework fossils are briefly discussed in the following chapter.

The two remaining framework categories are the oncolites and biolithites. The term oncolite is used here for unattached, subspherical, micrite-coated grains larger than 2 mm in diameter. These structures consist of a nucleus, usually a stromatoporoid fragment, that is coated by irregular layers of dense, micritic material (Plate 1, Figure 7). The outer, laminated material is interpreted to represent algal coatings, though the possibility of a non-organic origin cannot be ruled out.

The term biolithite is used for remains of the organic-reef where the framework organisms (largely stromatoporoids) are in growth position and form an intergrown, resistant, sediment binding structure (Plate 1, Figure 8). This rock type makes up only a small part of any reef complex and only a few examples of it were found in the Carson Creek North core.

(2) Grains (Particles between 2.0 and 0.03 mm):

Five major grain categories were recognized in the reef-complex limestones.

A lower size limit of 0.03 mm is used following Leighton and Pendexter (1962), as it is about the lower boundary for recognizing grains under the binocular microscope.

(a) Skeletal grains - The skeletal grains include both broken fragments and whole forms of shells or hard parts secreted by organisms (Plate II, Figures 1 and 2). They are the most abundant grains in the reef and reef flank areas, but are often subordinate to the non-skeletal grains in the back-reef areas. The more common bioclastic grains recognized are stromatoporoid, algal, coral, brachiopod, crinoid, and gastropod debris, as well as ostracode and foraminifera shells. Calcispheres are treated as a separate group, as are the algal-coated grains and the pellets, which may or may not be of fecal origin.

Skeletal grains are distinguished from non-skeletal grains on the basis of internal structure, shape, and color. Often they have a fibrous, lamellar, grid, or perforated structure that distinguishes them from non-skeletal grains, or they often have a characteristic shape that is related to their growth habit or internal microsctructure. Finally, skeletal grains are often more transparent and lustrous than non-skeletal grains and, in the case of the Carson Creek North complex, are usually grey to white in color in contrast to the yellowish brown color of the non-skeletal grains.

(b) Pellets - Grains classified as pellets consist of micritic or microcrystalline calcite, are devoid of significant internal structure, and are rounded to subrounded in shape. Where they are abundant, pellets are often well sorted, well rounded, and of very fine- to fine-sand size (Plate II, Figures 3 and 4). Following Klovan (1964), no size limit is placed on pellets other than the 0.03 to 2.0 mm grain boundaries.

PLATE II

Grain Types

Figure 1. Skeletal grains. Thin section of a biomicrite composed largely of brachiopod shell fragments, X9 (Location, 16-31-61-11, 8640').

Figure 2. Skeletal grains. Thin section of a skeletal calcarenite, X9 (Location, 16-31-61-11, 8544').

Figure 3. Pellets. Thin section of a pelsparite. Note recrystallized centers of many pellets, X28 (Locations, 6-11-62-12, 8875').

Figure 4. Pellets. Thin section of above pelsparite under lower magnification, X9 (Location, 6-11-62-12, 8875').

Figure 5. Intraclasts. Thin section of an intrasparite. Note the small spherulites showing radial extinction at the bottom of photograph, X22 (Location, 6-11-62-12, 8813').

Figure 6. Coated grains. Polished section in reflected light showing pellets and coated grains in a sparry matrix, X22 (Location, 6-11-62-12, 8813').

Figure 7. Calcisphere. Spined calcisphere in partially recrystallized micritic matrix, X55 (Location, 6-1-62-12, 9049').

Figure 8. Calcispheres. Calcispheres in a bituminous micritic matrix, X55 (Location, 6-1-62-12, 9049').

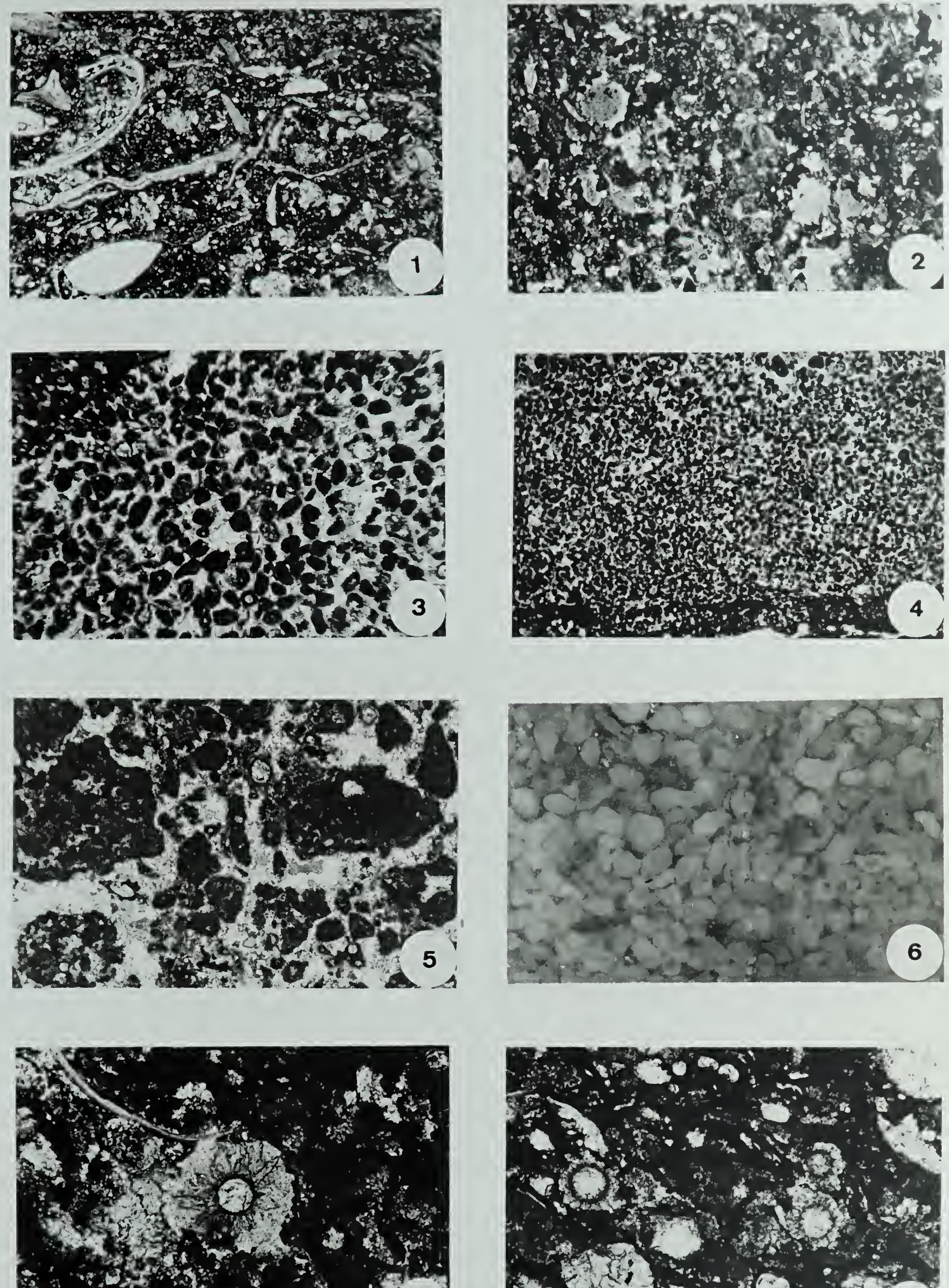


PLATE II.

Although a polygenetic origin for pellets is recognized no attempt is made here to determine their source. Many workers have thought that pellets are fecal deposits whereas others have suggested that they are formed largely through diagenesis, chemical precipitation, accretion, algal action, or that they represent rounded intraclasts. In the Carson Creek North limestones all gradations exist between distinct pellets and distinct intraclasts. It is thus probable that many grains considered here as pellets are rounded fragments of lime mud torn from the sea floor. For this reason, where pellets and intraclasts are hard to differentiate, or appear to be present in approximately similar amounts, the term intrapel is used as the basic rock name (see Table 3). This inability to always be able to distinguish pellets from intraclasts in ancient rocks has been noted by other workers such as Klovan (1964) and Jenik (1965).

(c) Intraclasts - The word intraclast is used here as a descriptive rather than a genetic term. It is used for non-skeletal grains that have either internal structure or angular or irregular shapes, or both (Plate II, Figure 5). This category excludes, however, the fragments with a definite coated or laminated surface such as the oölites and algal-coated grains, etc.,

No attempt is made to differentiate between lumps or composite grains formed by the process of aggregation and fragments formed by erosion of pre-existing rocks and sediments. By their character though, the majority of intraclasts are believed to represent, "fragments of penecontemporaneous, generally weakly consolidated carbonate sediment that have been eroded from adjoining parts of the sea bottom and redeposited to form a new sediment". (Folk, 1959, p. 4).

(d) Coated Grains - The writer follows Leighton and Pendexter (1962), p. 59) who define coated grains as, "grains possessing concentric or enclosing layers of calcium carbonate: for example oölites, pisolites, superficial oölites, and algal-encrusted skeletal grains".

True oölites are rare in the Carson Creek North limestones though grains resembling superficial oölites and spherulites are present in certain thin zones (Plate II, Figure 5). This scarcity of oölites in Alberta Devonian reef complexes has been noted by other workers such as Klovan (1964). The most abundant coated grains are the superficial oölites or so-called algal-coated grains (Plate II, Figure 6). These consist of a skeletal or non-skeletal nucleus that is surrounded by a thin, slightly laminated, micritic coating. This thin coating is probably algal in origin although it may represent chemical precipitation or mud accretion on a rolling fragment.

(e) Calcispheres - Calcispheres are small, spherical, calcareous structures that are a very common constituent of most Devonian reef-complex limestones. (Plate II, Figures 7 and 8). The size and ornamentation varies somewhat but they usually average about 0.1 - 0.2 mm in diameter and have a darker outer rim. Occasionally peripheral appendages and spines can be seen on well preserved forms. The central portion of the calcisphere is often hollow but may be filled with clear calcite. Although the exact origin or affinity of these spheroids is not known, most workers agree that they are organic and possibly algal. In the Carson Creek North reef complex, calcispheres are abundant and more or less restricted to the back-reef facies. This restriction is taken to indicate that they preferred quiet, shallow-water surroundings though it may only be a preservation phenomenon.

(3) Groundmass - Infill:

This major grouping of the textural components includes the micrite or carbonate sediment composed of grains less than 0.03 mm in diameter, the cement and infill, and the accessory or secondary minerals. These features are only briefly discussed here since they are also included in the section on diagenesis.

(a) Micrite - The term micrite is applied to the dull, brownish, somewhat opaque calcisiltite and lime mud whose grains have an upper size limit of 0.03 mm. This size limit differs from Folk's original definition of micrite but follows Leighton and Pendexter (1962), Murray (1966), and others. Micrite is a very important component in the back-reef and off-reef areas that are interpreted to represent relatively quiet water. The micrite: grain ratio shown in Table 3 is taken to be an indication of the water energy in the environment of deposition.

The origin for the micrite found in both recent and ancient limestones is debatable. In the limestones of this report a good part of it at least has been formed by the alteration, abrasion, and disintegration of skeletal fragments. Also, the compaction or squeezing together of pellets and intraclasts into a tight, micritic-looking rock has been observed.

(b) Sparry calcite - Sparry calcite includes all the translucent, lustrous, calcite crystals that occur as void filling cement or as a recrystallization product. Crystal size is not used here as a criterion of definition, though most of the spar is relatively coarse. Evidence for both authigenic precipitation of spar in voids and spar formed by the recrystallization of pre-existing carbonate can readily be found

in the limestones. For a thorough discussion on the origin, character, and time of emplacement of the various types of sparry calcite the reader is referred to Bathurst (1958) and Folk (1965).

(c) Dolomite - Dolomite is a common accessory mineral and is especially evident in the more porous reef-flank rocks. It is very often associated with, and is similar to, the sparry calcite. It occurs as isolated rhombs in the matrix, as void filling cement, and as a recrystallization or replacement product. Staining and etching were used to differentiate between dolomite and calcite spar. Nowhere in any of the core studied was there anything approaching complete dolomitization of the rock. The dolomite, as most of the other textural components of the complex, has a variety of occurences, and therefore probably did not have a single, simple mode of origin.

(d) Argillaceous Material - Though many of the reef complex limestones are dark in color the argillaceous content is normally very small. The dark color is largely due to varying amounts of organic residue present. The only notable accummulation of clay minerals is in the green shale marker and green shale lenses. According to Murray (1965, p. 57), illite and rare chlorite are the chief clay minerals in the green shale zones. In the off-reef Waterways Formation, however, there is a considerable argillaceous content.

(e) Chert and Quartz - Silica in the form of quartz and chert is a rare but interesting component in the Swan Hills carbonates. In the present study it was found only in the off-reef and fore-reef beds though possibly a closer examination would reveal it in the back-reef areas as well. The quartz usually occurs as euhedral to sub-

hedral crystals associated with and replacing large skeletal allochems. The chert is found associated with the quartz crystals, but also occurs separately in small dark lenses or patches.

(f) Pyrite is a common accessory mineral found in nearly every rock type of the complex. It is especially common at the top of the reef, in the darker or more argillaceous rocks, and in association with stylolites and fractures, etc., It occurs as a replacement mineral of fossils, as a void filling precipitate, as an insoluble residue deposit, and, in the Waterways Formation, sometimes occurs in layers parallel to the bedding and may represent a sedimentary deposit.

(g) Anhydrite - Most publications on Swan Hills carbonates report anhydrite as being one of the accessory minerals. In the Carson Creek North core only a few examples of void filling anhydrite were found. Much material originally thought to be anhydrite proved to be dolomite on closer examination.

(h) Stylolites - Stylolites are very common and are believed to be of more than one type with different modes of origin. They range in color from green to brown to black and differ quite considerably in form and size.

(i) Porosity - Porosity or void space is a common feature of the reef and reef-flank rocks but not of the rocks in the central parts of the complex. Thomas (1962), showed how the Swan Hills complexes can be mapped on the basis of porosity and permeability values.

CHAPTER 5 - PALEONTOLOGY

General Statement

Fossils, both whole and fragmentary, are the most important constituents of the reef complex. The type, relative abundance, and ecological significance of the fossils is discussed. Although generic and specific identifications were attempted for as many forms as possible it is stressed that they may be subject to change with more detailed study.

Preservation varies depending upon the fossil type and the nature of the supporting lithology. The fossils are composed of calcite except for the few chitinophosphatic fragments and inarticulate brachiopods found in the Waterways Formation. Dolomite, pyrite, and silica replacement occurs, but it is not common and usually does not destroy the structures. Most of the calcite fossils have undergone some recrystallization.

The fossil assemblages found in the reef complex are believed to be primarily facies controlled. This belief, along with the few precise identifications at the species level, makes exact age determinations and regional correlation difficult. The fossils are, however, extremely useful for mapping facies, and for environmental interpretations.

Fossils

Stromatoporoids:

Stromatoporoids are an extinct group of organisms whose skeletons consist of

thin calcareous laminae, pillars, and curved plates. They are believed to have been colonial, benthonic, and sessile; and to have preferred clear, shallow, warm water similar to that found on modern tropical banks and reefs. Though widespread and relatively abundant, stromatoporoids have not received enough detailed study, and their exact origin, biological affinities, growth habits, and taxonomy are not well known.

In the Carson Creek North reef complex, stromatoporoids are by far the most abundant and widespread of all fossils. They occur in all geographical areas, in all rock types, and assume a wide variety of shapes and sizes. It is believed that this extreme diversity of shape and size allowed the stromatoporoids to fill most of the ecological niches that the rigid corals, calcareous algae, and hydrozoans occupy in present-day reefs. During the petrographic study the stromatoporoids were designated as being one of the following: massive, tabular, bulbous, or branching. Within the branching group, Amphipora and Stachyodes were separated. For identification purposes about 30 stromatoporoid specimens were thin sectioned and studied in detail (see Plates III to VI). Amphipora, Stachyodes, Trupetostroma, Stromatopora, and Clathrocoilona appear to be the most abundant genera present in the reef complex, and examples of four of the five stromatoporoid families as proposed by Galloway (1957), have been found.

It is evident that most stromatoporoids were able to assume highly variable shapes and sizes depending upon where they were growing. It may be, therefore, that the shape and size of the coenostea are more useful for environmental reconstruction than are specific identifications. Since stromatoporoids are believed to have

PLATE III

Massive Stromatoporoids - Swan Hills Formation
(Thin section identifications)

Figures 1,2. *Stromatopora* sp. 1, vertical section; 2, tangential section. X22 (Location, 16-6-62-11, 8833').

Figures 3,4. *Ferestromatopora* sp. 3, vertical section; 4, tangential section. X22 (Location, 6-32-61-11, 8714').

Figures 5,6. *Stromatopora* cf. *cygnea*. 5 vertical section; 6, tangential section. X9 (location, 6-1-62-12, 8943').

Figures 7,8. *Gerronostroma* sp. 7, vertical section; 8, tangential section. X9 (Location, 6-4-62-12, 8480').

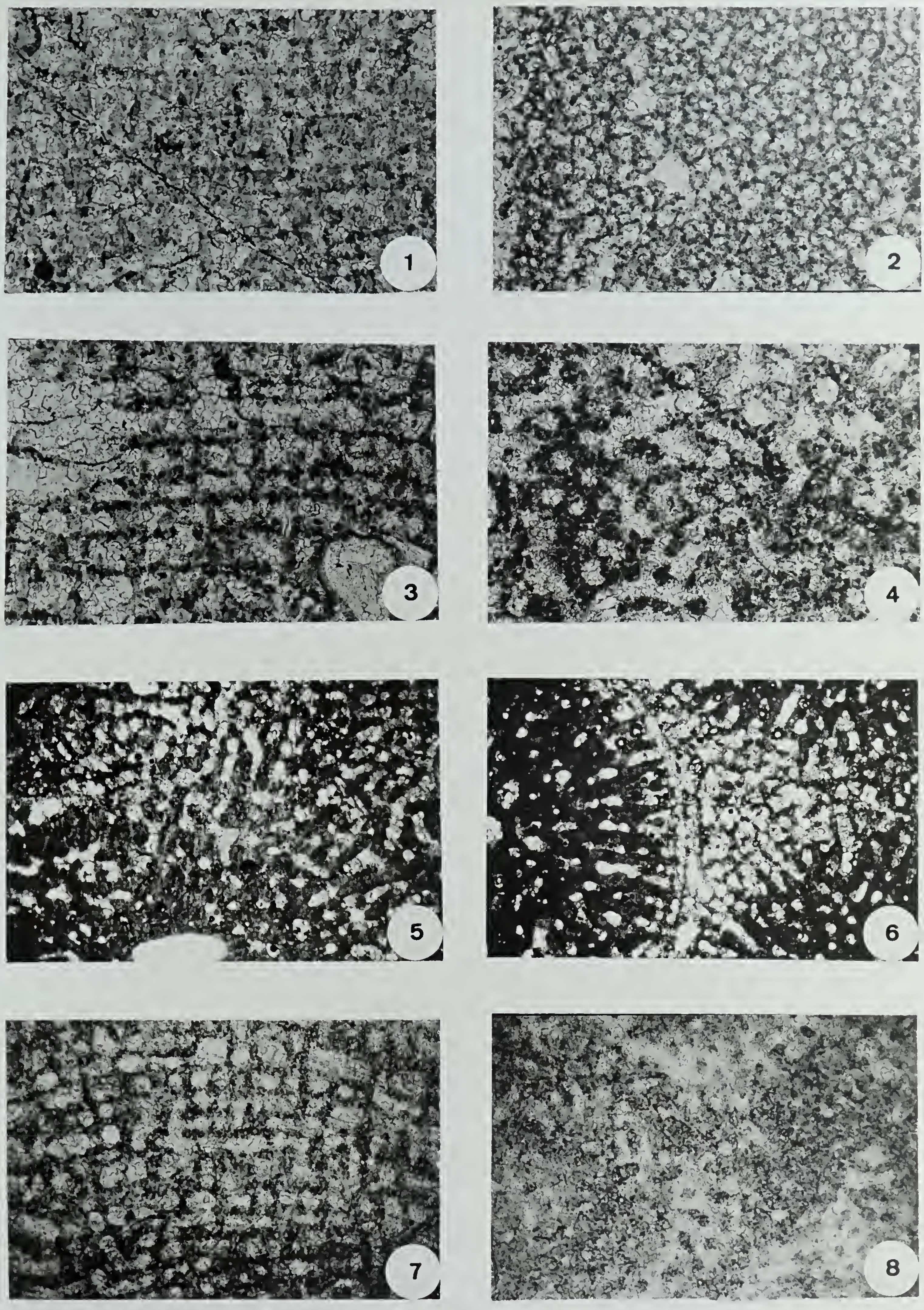


PLATE III.

PLATE IV

Massive Stromatoporoids - Swan Hills Formation
(Thin section identifications)

Figures 1,2. Anostylostroma? sp. 1, vertical section; 2, tangential section. X9 (Location 6-11-62-12, 8825').

Figures 3,4. Trupetostroma lecomptei. 3, vertical section; 4, tangential section. X9 (Location, 6-1-62-12, 8772').

Figures 5,6. Trupetostroma cf. warreni. 5, vertical section; 6, tangential section. X9 (Location 6-1-62-12, 8932').

Figures 7, 8. Clathrodictyon ? sp. 7, vertical section; 8, tangential section. X9 (Location, 6-36-61-12, 8473').

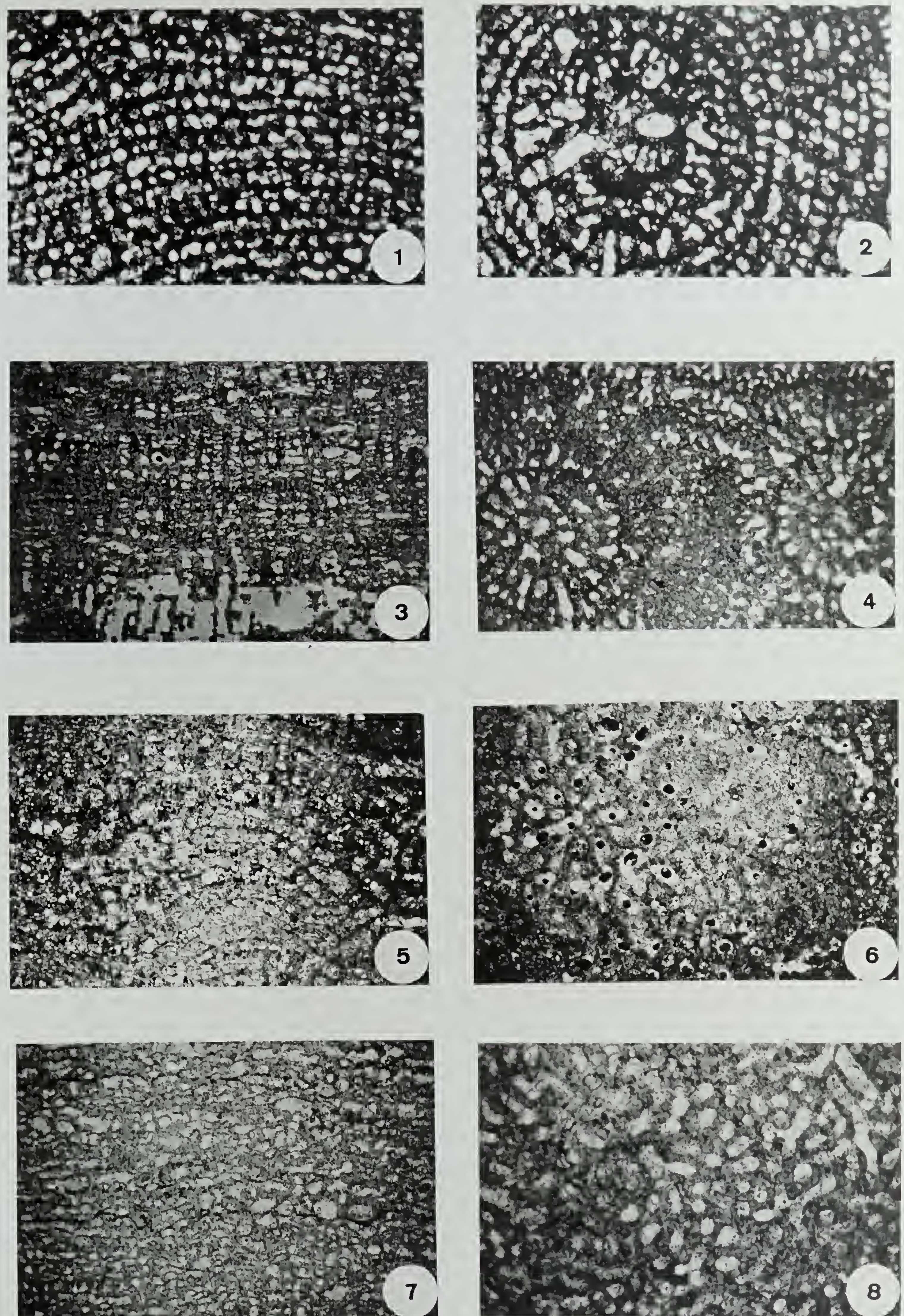


PLATE IV.

PLATE V

Tabular Stromatoporoids - Swan Hills Formation
(Thin section identifications)

Figures 1,2. Syringostroma? cf. confertum. 1, vertical section; 2, tangential section. X9, (Location 16-31-61-11, 8600').

Figures 3,4. Clathrocoilona inconstans. 3, vertical section; 4, tangential section. X9 (Location, 16-31-61-11, 8638').

Figures 5,6. Stromatopora cf. cygnea. 5, vertical section; 2, tangential section. X9 (Location, 16-6-62-11, 8788').

Figures 7,8. Trupetostroma lecomptei. 7 vertical section; 8, tangential section. X22 (Location 6-1-62-12, 8937').

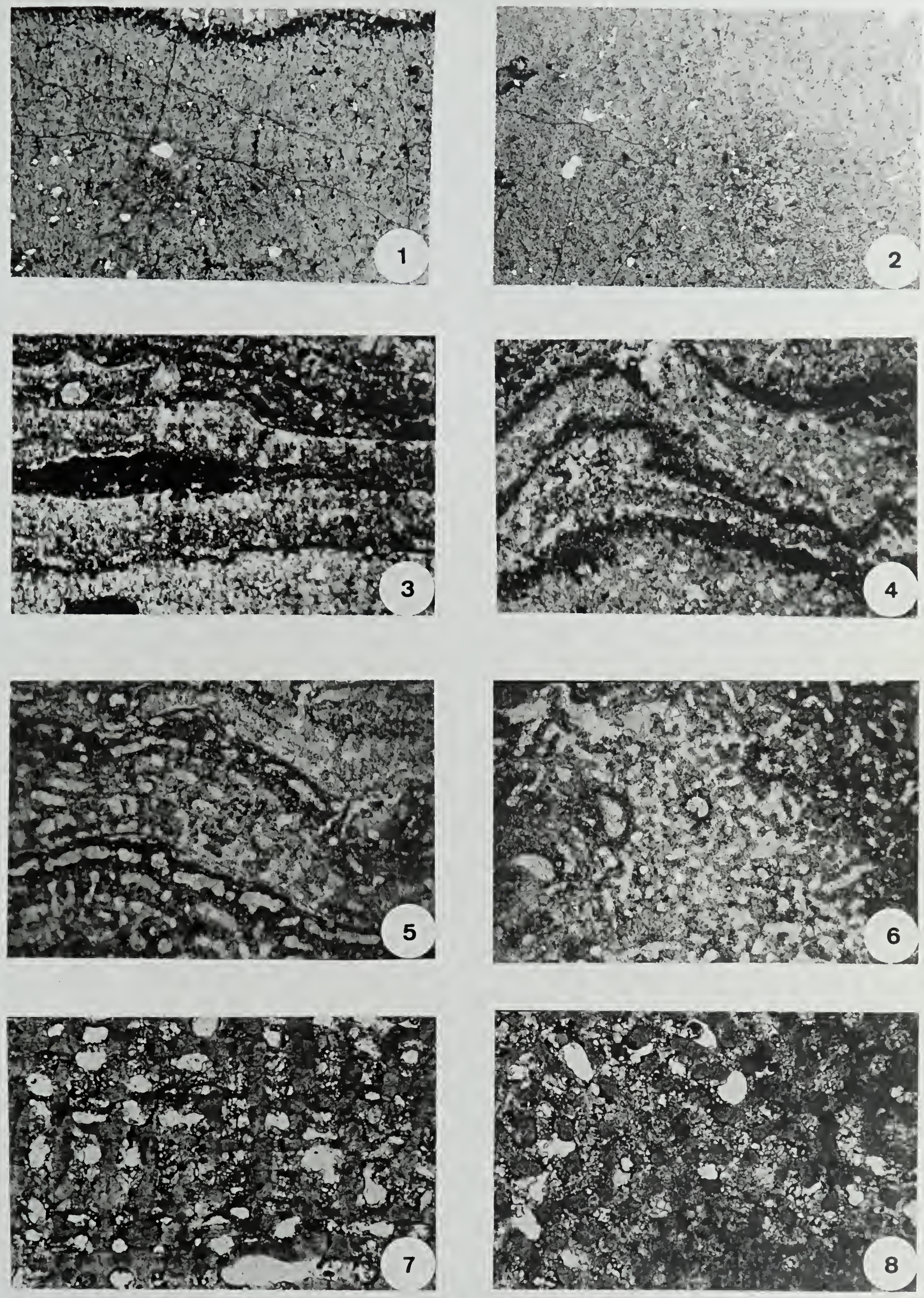


PLATE V.

PLATE VI

Tabular and Dendroid Stromatoporoids - Swan Hills Formation
(1-7, thin sections; 8, acetate peel)

Figures 1,2. Taleastroma? cf. confertum. 1 vertical section; 2 tangential section. X9 (Location 16-31-61-11, 8616').

Figures 3,4. Stachyodes sp. 3, vertical section; 4, tangential section. X9 (Location 16-31-61-11, 8660').

Figures 5,6. Euryamphipora sp. 5, vertical section; 6, tangential section. X9 (Location 6-1-62-12, 9049').

Figure 7. Amphipora cf. ramosa. oblique section X9 (Location 16-5-62-12, 8627').

Figure 8. Amphipora sp. random sections; acetate peel, negative photograph. X2 (Location 6-1-62-12, 8826').

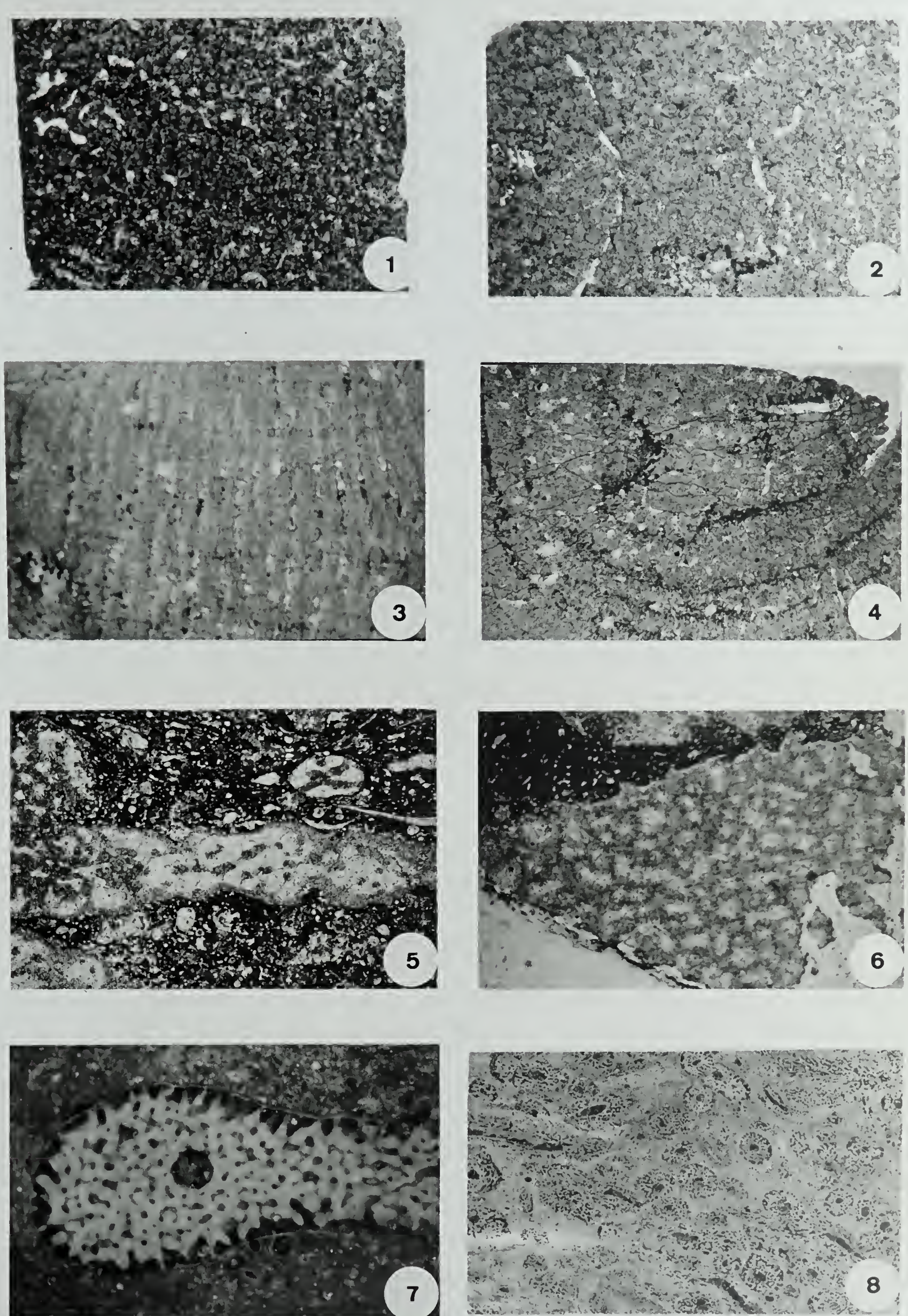


PLATE VI.

been sessile and largely environment dependent, one would not expect them to be of value in world-wide correlations. St. Jean (1960), however, found that certain microstructures occur in geographically widespread species of similar age, and are of stratigraphic value. Stromatoporoids, therefore, may be one of the most valuable fossil groups available for deciphering the sedimentation history, age, and correlation of Devonian reef complexes, and should receive more detailed study in the future.

Massive Stromatoporoids

Considered as massive stromatoporoids are all dome-shaped or subspherical forms whose height or vertical dimensions are approximately equal to their width or horizontal dimensions. (Plate VII, Figures 1 and 2). Except in the biolithites, these organisms have not been found in growth position and are usually fragmented and associated with coarse skeletal debris. Besides shape, arcuate laminae and latilaminae characterize these forms, along with the large size which they can attain.

Massive stromatoporoids occur most commonly in the organic-reef and reef-detritus facies, characterizing the outer rim of the reef complex. They are interpreted as being the major reef builder in the complex and one well (16-6-62-11W5) contains approximately a 10 foot interval of massive stromatoporoids growing on top of each other. About 20 feet of core in this well is interpreted as representing _in situ_ organic-reef.

Trupetostroma appears to be the most abundant massive stromatoporoid in the Carson Creek North field but _Stromatopora_, _Gerronostroma_, _Anostylostroma_? and other genera have been found (see Plates III and IV). Tabular stromatoporoids, _Stachyodes,_

Plate VII

Stromatoporoid Types
(Peels are negative photographs)

Figure 1. Massive stromatoporoids. Peel showing rounded and abraded massive stromatoporoid fragments in a coarse matrix, X0.8, (Location, 6-1-62-12, 8919').

Figure 2. Massive stromatoporoid. Peel showing large laminated massive stromatoporoid cut by core, X0.8 (Location, 6-36-61-12, 8501').

Figure 3. Tabular stromatoporoids. Peel showing tabular stromatoporoids in postulated growth position in a micritic groundmass, X0.8 (Location, 16-6-62-11, 8865').

Figure 4. Tabular stromatoporoids. Peel showing fragmented tabular stromatoporoids in biomicrite groundmass, X0.9 (Location, 16-31-61-11, 8618').

Figure 5. Bulbous stromatoporoid. Hand specimen showing bulbous stromatoporoid with concentric growth rings. Note the thin micritic coating (algal?) X 0.7 (Location, 6-11-62-12, 8698').

Figure 6. Dendroid stromatoporoids. Hand specimen showing dendroid stromatoporoids, largely Amphipora, many of which are algal coated, X 0.7 (Location 16-6-62-11, 8840').

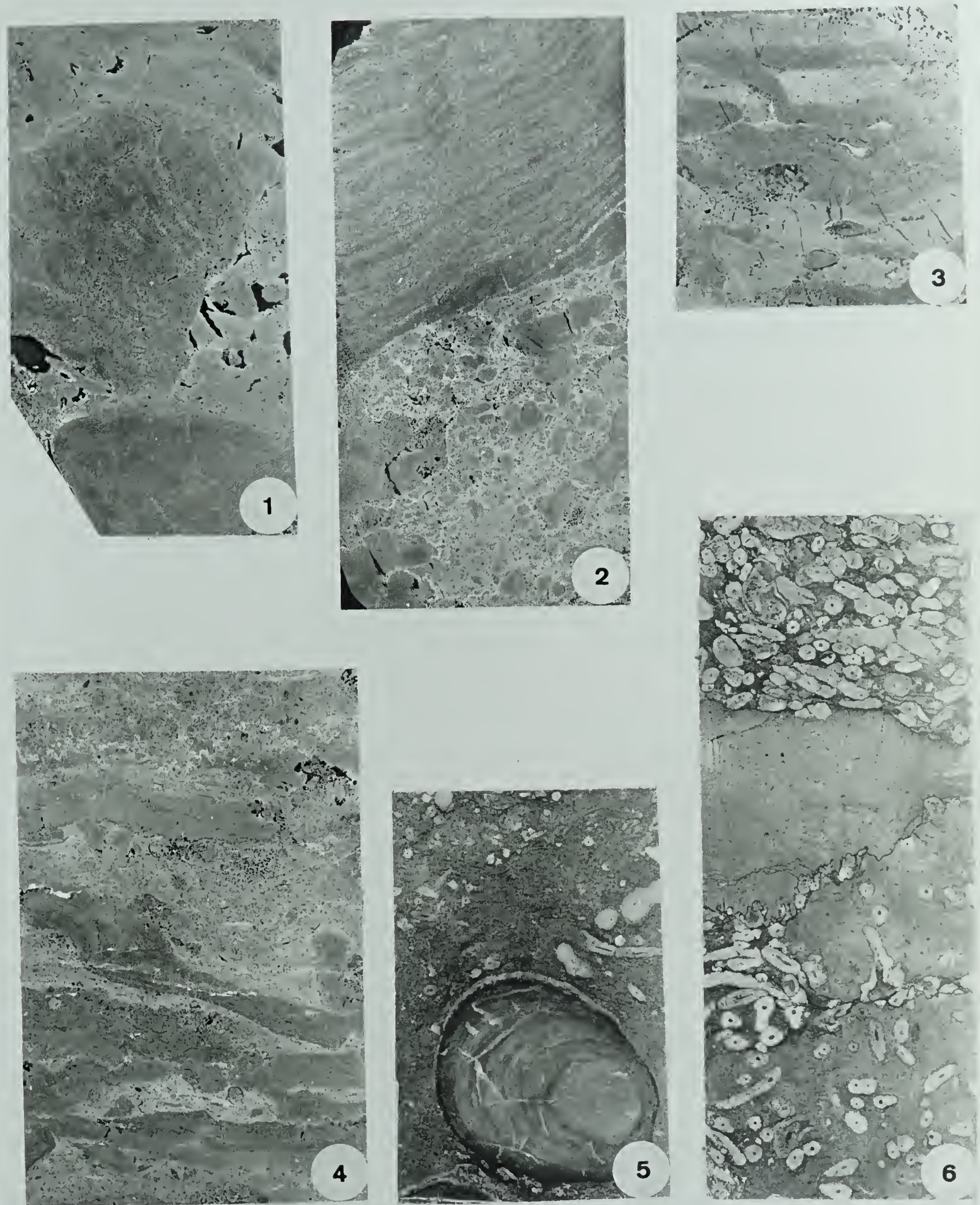


PLATE VII.

crinoids, corals, brachiopods, and solenoporoid algae are the fossils most commonly found associated with the massive stromatoporoids.

Massive stromatoporoids are interpreted as having favoured a clear, turbulent, shallow-water environment. Being the principal frame-builder in the organic lattice they are considered to have been wave resistant when growing. Whether they actually grew into the surf zone or were partially exposed at low tide is not known.

Tabular Stromatoporoids

Tabular or "pancake-shaped" stromatoporoids are flat (usually less than two inches thick) and spread out laterally to several times their thickness (Plate VII, Figures 3 and 4). Curved laminae and latilaminae are not so evident as in the massive types, and there is less distinction between pillars and laminae. Many tabular stromatoporoids have been seen in apparent growth position, and, as pointed out by Klovan (1964, p. 36), they often form a base and branch outward and upward over sediment that has partially covered them (Plate VII, Figure 3). Occasionally specimens appear to be transitional between the massive, tabular, or dendroid shapes; that is, certain genera can take on a variety of external shapes depending upon the nature of their environment.

Tabular stromatoporoids are most abundant in the fore-reef limestones, are common in the reef facies, and are rare to absent in most back-reef rock types. On certain parts of the fore-reef slope it appears that tabular stromatoporoids in association with solenoporoid algae formed prolific organic communities. These grew in much quieter water than the massive stromatoporoid organic-reefs but were probably

resistant to considerable wave and current action.

Stromatopora, Clathrocoilona, and Taleastroma are the most common tabular-shaped genera found in the thin sections studied (see Plates V and VI). Solenoporoid algae, brachiopods, Stachyodes, and massive stromatoporoids are commonly found in the same rocks as the tabular stromatoporoids.

The tabular stromatoporoids in the Carson Creek North complex apparently could live in both turbulent and moderately quiet, clear waters but thrived best in the latter environment. Murray (1966, p. 17) considers that the tabular stromatoporoids grew in the lower part of the zone of vigorous photosynthesis whereas the massive type grew in the upper part of this zone. The writer agrees that the tabular stromatoporoid appears to have been a deeper, quieter-water form than the massive stromatoporoid.

Bulbous Stromatoporoids

Following Murray (1966), this category includes all spherical and oblate forms approximately 2 to 8 cm. in diameter (Plate VII, Figure 5). Cross sections of these types consist of concentric traces of laminae that gives the form a "cabbage-head" appearance.

In contrast to the massive and tabular types, bulbous stromatoporoids are most common in the reef platform and in the back-reef facies. Murray (1966) suggested that the bulbous stromatoporoids lived in quiet, restricted waters. However, since most forms are well-rounded, show no means of attachment, and are often coated

with a thin layer of micritic or algal material (see Plate VII, Figure 5) it is possible that they lived in a more turbulent-water environment and after death became eroded and transported by rolling to more quiet waters.

Dendroid Stromatoporoids

Included in this group are the rod-shaped, ramose, or finger-shaped stromatoporoids belonging to the family Idiostromatidae (Plate VII, Figure 6). For the purpose of this study the dendroid forms have been separated into two groups; those belonging to the genus *Amphipora* (Plate VIII, Figures 1 to 6), and those to the genus *Stachyodes* (Plate VIII, Figures 7 to 8). *Idiostroma* and other dendroid stromatoporoids are very similar in appearance and association to *Stachyodes* and were not distinguished separately.

(a) *Amphipora* - *Amphipora* fragments are the most abundant fossils found in the Carson Creek North reef complex. This distinctive stromatoporoid is characterized by its rod-shaped skeleton that is usually less than 5 mm in diameter, by its large axial tube and marginal vesicles, and by the character of its transversely fibrous tissue with median line (Plate VIII, Figure 4).

The growth position of *Amphipora* is unknown, but it probably grew upright with its long axis vertical. A few specimens have been found this way but it is difficult to tell if they are in growth position or not. Most forms are found flat-lying with their long axis more or less parallel to the stratification. Calcirudites, composed almost entirely of intertwinned and fragmented *Amphipora* stems (Plate XVI, Figure 5)

PLATE VIII

Amphipora and Stachyodes

Figure 1. Juvenile Amphipora. Polished section (reflected light) showing Amphipora in various stages of growth, X10 (Location, 16-5-62-11, 8643').

Figure 2. Amphipora. Polished section (reflected light) showing an Amphipora coenostea with two axial canals; possibly due to sectioning near the base of two branches, X8, (Location, 16-6-62-11, 8840').

Figure 3. Branching Amphipora. Peel showing branching Amphipora in various states of preservation, X0.7 (Location 16-6-62-11, 8840').

Figure 4. Amphipora. Polished section (reflected light) of an Amphipora stem that shows three small cysts or buds attached to the upper surface of the coenostea, X9 (Location, 16-5-62-12, 8627').

Figure 5. Amphipora. Enlargement of Figure 4 above to show nature of cysts or buds, X22 (Location, 16-5-62-12, 8627').

Figure 6. Euryamphipora. Hand specimen showing the "pancake" shaped Euryamphipora, X0.7 (Location, 16-5-62-11, 8647').

Figure 7. Stachyodes. Hand specimen showing fragmented Stachyodes stems in a biomicritic groundmass, X0.75 (Location, 16-6-62-11, 8714').

Figure 8. Stachyodes. Hand specimen showing Stachyodes in postulated growth position, X0.75 (Location, 16-6-62-11, 8825').

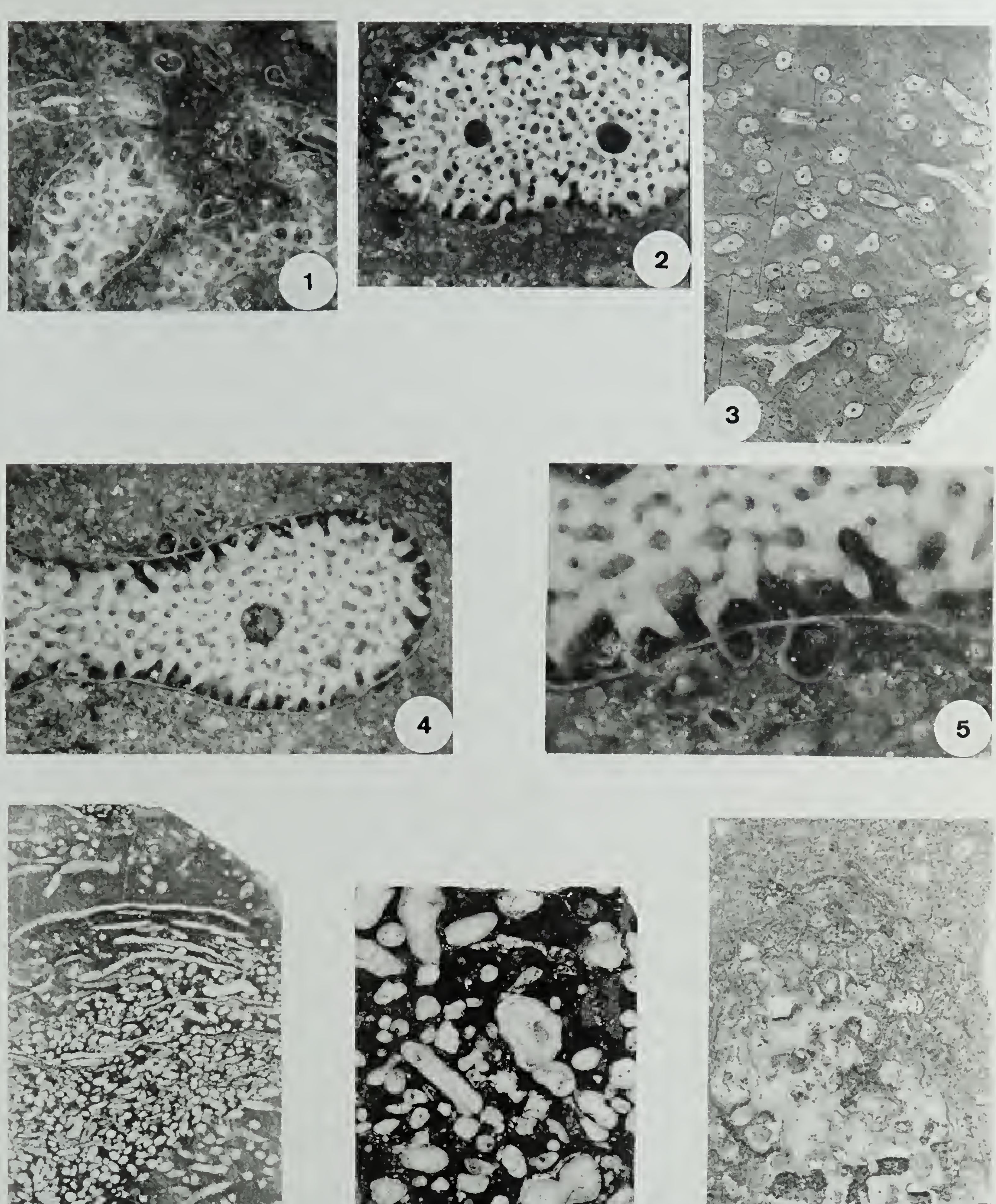


PLATE VIII.

have been found and may represent Amphipora thickets in growth position, or just clastic accumulations of transported Amphipora fragments. The latter possibility is favoured here,and because of their close association with postulated supratidal and intertidal sediments they are interpreted to represent beach or strand line deposits.

If Amphipora grew in an upright position, the skeletal part we find preserved probably did not penetrate below the depositional interface. If the skeleton itself was rooted in the substratum, one would expect to find many more forms in growth position in the quiet-water environments. It is possible that soft, living tissue formed the roots and means of attachment; after death this would be unable to support the vertical stems which would topple over and be preserved in a horizontal position. Storms or vigorous wave and current action might also have broken or ruptured many Amphipora at the soft basal attachment causing them to topple over and die.

Reproductive methods as well as growth habits are unknown for Amphipora. It is possible that the branching forms were the result of asexual reproduction whereby budding occurred. The bud probably remained with the parent, secreted a skeletal base and became permanently attached to form a separate branch. Numerous examples of peripheral buds or cysts and branching have been found on Amphipora coenostea (Plate VIII, Figures 2 to 5). From the large numbers of small, separate juvenile Amphipora (Plate VIII, Figure 1) and unbranched adults found, though, it appears that if budding was the principal form of reproduction, most buds broke away from the parents early to settle down and grow as separate forms elsewhere.

Though found scattered in all rock types, Amphipora occurs predominantly in the back-reef deposits or central portions of the reef complex. As pointed out by

Murray (1966, p. 19), Amphipora individuals were not reef-builders but may have been important as baffles for trapping sediment, and their hard parts contributed a large amount of skeletal material as sediment. It is proposed that Amphipora thrived and grew in abundance only in relatively quiet, sheltered waters. Though a good indication of back-reef facies they are not restricted to that environment, and could grow in any place that had similar conditions. Their abundance in the biostromal reef platform illustrates the fact that a lagoonal or back-reef interpretation cannot always be applied to fine-grained rocks containing numerous Amphipora stems.

An interesting tabular or "pancake-shaped" Amphipora was found in the reef platform (Plate VIII, Figure 6). This form has been noted by Murray (1966, p. 19) in the Judy Creek field and by Jenik, (1965, p. 35) in the Goose River field. Jenik (1965) calls this form "Euryamphipora" following Klovan (1963).

(b) Stachyodes - Stachyodes occurs as stubby, cylindrical branches that have an average diameter of about 1 cm. Stachyodes can be distinguished from Amphipora by having a lack of marginal vesicles and large axial canal, and by being composed largely of tissue with only small galleries. Also, Stachyodes is usually larger and less well preserved than Amphipora. Usually Stachyodes consists of broken fragments (Plate VIII, Figure 7), but some branching "bush-like" colonies have been found growing from a common base that are interpreted as being in growth position (Plate VIII, Figure 8).

Stachyodes characterizes the reef and fore-reef facies. They are associated with massive stromatoporoids in the organic-reef; massive stromatoporoids and Amphipora

in the back-reef detritus; and with crinoids, corals, tabular stromatoporoids, solen-oporoid algae, and brachiopods in the fore-reef detritus. It is concluded that Stachyodes preferred clear, moderately turbulent, open marine waters and thus grew in abundance on the organic-reef and upper portions of the fore-reef slope.

Corals:

Corals are not abundant in the Carson Creek North field and have been grouped into two main categories; the colonial tabulate corals and the solitary rugose cup corals. Only a few of the encrusting types have been found in growth position. No detailed study was made of the corals and only a few forms have been identified at the generic level. (Plate XII, Figures 20-34).

Thamnopora, used here to include forms sometimes known as Cladopora and Coenites, is the most important coral found in the Swan Hills reef complexes. Fragments of this branching tabulate coral are common in the reef and fore-reef rocks associated with stromatoporoids, especially Stachyodes, and coarse skeletal debris. Thamnopora also occur in the rocks of the reef platform, being especially plentiful in the so-called "coral bed" of Fong (1960).

These corals are interpreted to have lived in well aerated, moderately turbulent, shallow waters . The colonial tabulate corals are not considered to have been a major reef-building organism in the Swan Hills reef complexes.

Solitary rugose cup corals occur sporadically throughout the complex but were never found in any great abundance. Stereolasma, Metriophyllum,? and

PLATE IX

Brachiopods and Pelecypod (Waterways Formation)

Figures 1-4.	Ambocoelia? cf. umbonata, X2 (Location 16-31-61-11, 8490'). Dorsal, ventral, posterior, and lateral views.
Figures 5-7.	Martinia? richardsoni X2, (Location, 16-31-61-11, 8490'). Dorsal, ventral, and posterior views.
Figure 8.	Chonetes? sp. X2, (Location, 16-31-61-11, 8508'). Dorsal view.
Figures 9-13.	Calvinaria cf. albertensis X2 (Location, 16-5-62-11, 8603'). Dorsal, ventral, lateral, posterior, and anterior views.
Figures 14-16.	Atrypa cf. albertensis X2 (Location 16-5-62-11, 8603'). Dorsal, lateral, and posterior views.
Figures 17, 18.	Athyris sp. X2 (Location 16-5-62-11, 8603'). Dorsal and ventral views.
Figures 19-22.	Cranaena sp. X6 (Location, 16-5-62-11, 8603'). Dorsal, ventral, lateral, and posterior views.
Figures 23, 24.	Calvinaria? sp. X6 (Location 16-5-62-11, 8603'). Dorsal and lateral views.
Figure 25.	Eleutherokomma cf. jasperensis X5 (Location, 16-31-61-11, 8508'). Dorsal view.
Figure 26.	Lingula cf. melie X25 (Location 16-31-61-11, 8490'). Dorsal view.
Figure 27.	Lingula cf. spatula X25 (Location 16-31-61-11, 8490'). Displaced dorsal and ventral valves.
Figures 28, 29.	?Craniops? sp. X20 (Location, 16-31-61-11, 8490'). Dorsal views.
Figure 30.	?Ontaria? sp. X15 (Location, 6-32-61-11, 8625'). Cast of dorsal valve of specimen.

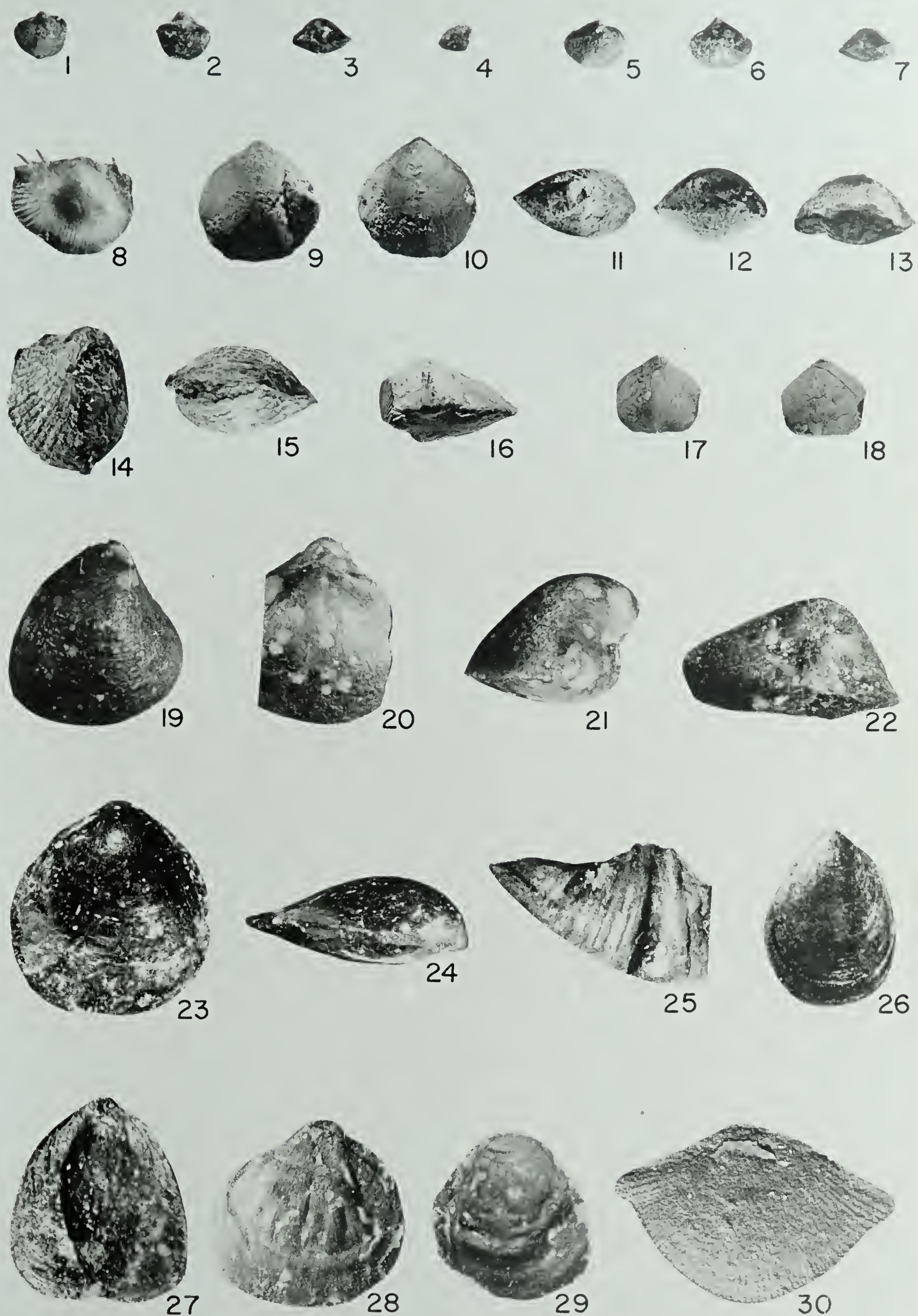

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PLATE IX.

PLATE X

Brachiopods - Swan Hills Formation

Figures 1-5. Athyris cf. vittata X2 (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 6,7. Atrypa cf. andersonensis X2 (Location 6-32-61-11, 8676'). Dorsal and lateral views.

Figures 8-12. Atrypa sp. X2 (Location 6-36-61-12, 8645'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 13-16. Atrypa albertensis X2 (Location, 16-31-61-11, 8638'). Dorsal, ventral, lateral, and posterior views.

Figures 17-20. Cranaena sp. X2 (Location, 16-6-62-11, 8808'). Dorsal, ventral, lateral, and posterior views.

Figures 21-23. Stropheodonta? sp. X2 (Location, 6-32-61-11, 8660'). Dorsal and ventral views.

Figures 24-26. Atrypa cf. independensis X2 (Location 6-32-61-11, 8660'). Dorsal, lateral, and posterior views.

PLATE X.

PLATE XI

Brachiopods - Swan Hills Formation
(All specimens X2)

Figures 1-5. Cyrtina sp. (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 6-9. Cranaena? sp. (Location 6-11-62-12, 8840'). Dorsal, ventral, lateral, and posterior views.

Figures 10-13. Atrypa? sp. (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, and posterior views.

Figures 14-18. Atrypa? sp. (Location 16-6-62-11, 8808'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 19-23. Cranaena sp. (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, posterior and anterior views.

Figures 24,25. Cranaena? sp. (Location 6-32-61-11, 8682'). Dorsal and ventral views.

Figure 26. Atrypa? sp. (Location 6-32-61-11, 8676'). Dorsal view.

Figures 27-30. Cranaena sp. (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, and posterior views.

Figures 31-33. Cranaena sp. and Spirorbis sp. epifauna (Location 16-6-62-11, 8770'). Dorsal, lateral, and posterior views.

Figures 34-38. ?Athyrid? brachiopod (Location 6-32-61-11, 8676'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 39,45,46. Productella sp. (Location 16-6-62-11, 8808'). Dorsal, lateral, and posterior views.

Figures 40-44. Athyris cf. vittata. (Location 6-32-61-11, 8676'). Dorsal, ventral, lateral, posterior, and anterior views.

Figures 47-58. Atrypa, cf. albertensis. (Location 16-6-62-11, 8793').
47-50. Dorsal, ventral, lateral, and posterior views.
51-53. Dorsal, ventral, and lateral views.
54-58. Dorsal, ventral, lateral, posterior, and anterior views.

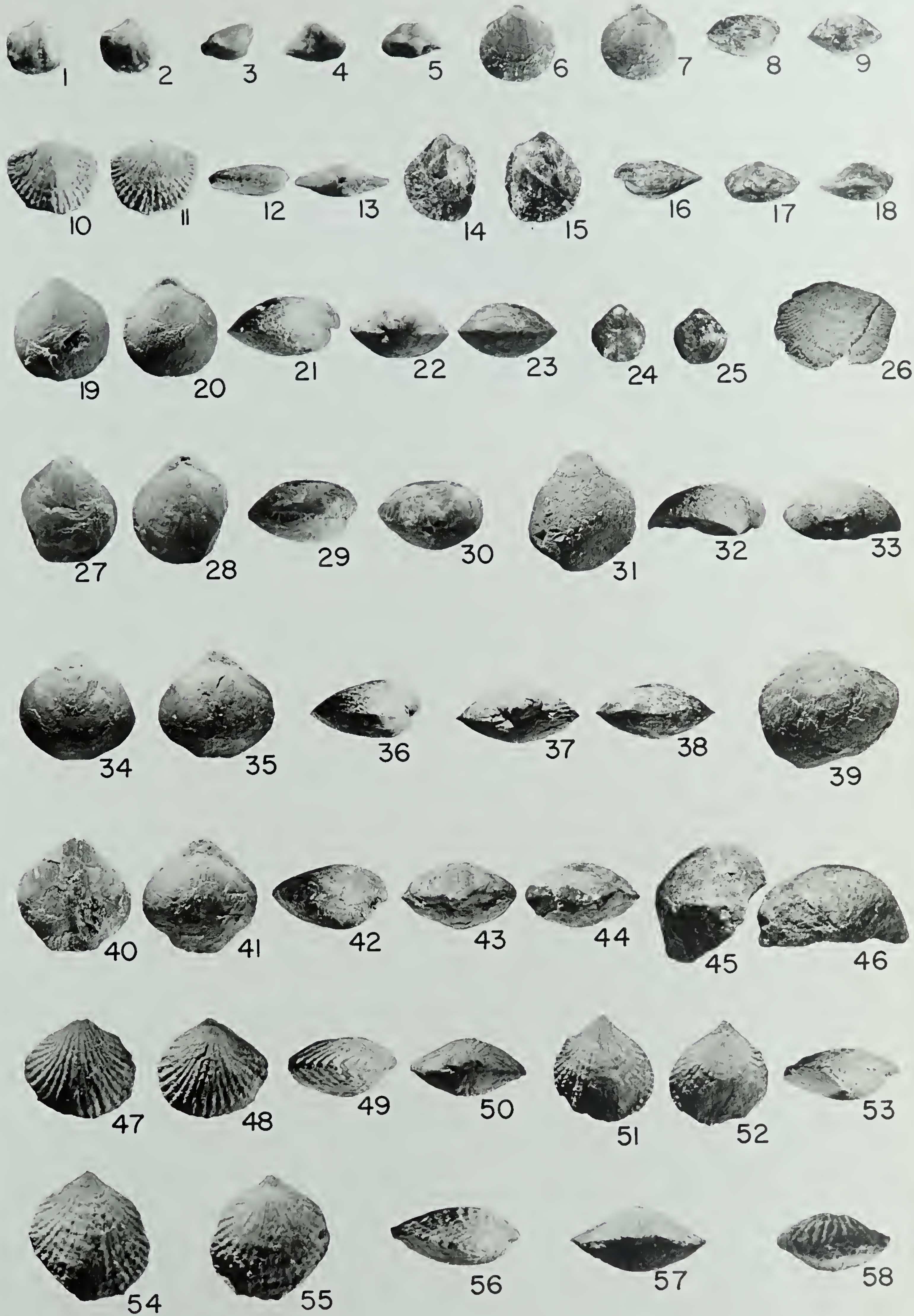
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PLATE XI.

PLATE XII

Brachiopods and Corals - Swan Hills Formation

Figures 1,2.	Schizophoria sp. X2 (Location 16-6-62-11, 8808'). Dorsal views.
Figures 3,4.	Atrypa sp. X2 (Location 6-32-61-11, 8676'). Dorsal and lateral views.
Figures 5-8.	Atrypa sp. X2 (Location 16-6-62-11, 8793'). Dorsal, ventral, lateral, and posterior views.
Figure 9.	Atrypa sp. X2 (Location 6-32-61-11, 8676'). Dorsal view.
Figures 10-13.	Atrypa cf. albertensis X2 (Location 16-6-62-11, 8808'). Dorsal, ventral, lateral, and anterior views.
Figure 14.	Schizophoria cf. iowaensis X2 (Location 16-6-62-11, 8793'). Dorsal view of broken specimen.
Figures 15-19.	Atrypa sp. X2 (Location 16-6-62-11, 8808'). Dorsal, ventral, lateral, posterior, and anterior views.
Figures 20-26.	Stereolasma? sp. X1
20	Location 6-36-61-12, 8486'.
21	Location 6-36-61-12, 8614'.
22	Location 6-32-61-11, 8682'.
23	Location 6-36-61-12, 8654'.
24	Location 6-32-61-11, 8688'.
25, 26.	Location 6-36-61-12, 8654'.
Figure 27.	Thamnopora sp. (encrusted by a stromatoporoid) X1 (Location 6-36-61-12, 8576').
Figure 28.	Tabulophyllum? sp X1 (Location 16-31-61-11, 8540').
Figure 29.	Thamnopora sp. X1 (Location 6-36-61-12, 8580').
Figure 30.	?Tabulophyllum? sp. X1 (Location 6-32-61-11, 8699').
Figure 31.	?Alveolites? sp. X0.7 (Location 16-31-61-11, 8575').
Figure 32.	Stewartophyllum? sp. transitional to Metriophyllum? sp. X5 (Location 16-31-61-11, 8639').
Figure 33.	Thamnopora sp. X1 (Location 16-6-62-11, 8736').
Figure 34.	Tabulophyllum? sp. X2 (Location 6-32-61-11, 8699').

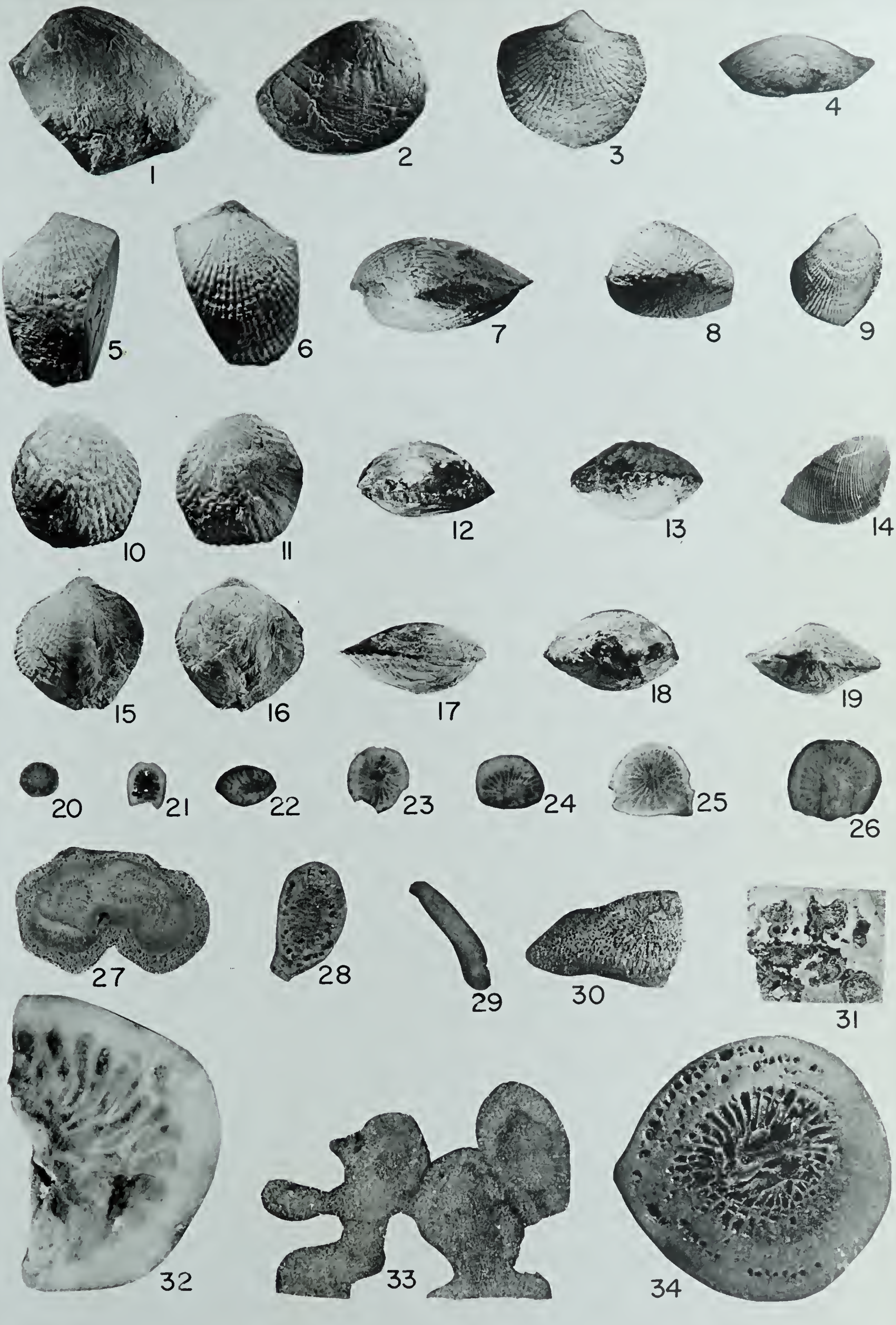
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PLATE XII.

PLATE XIII

Miscellaneous Fossils

(Figures 1-11, Waterways Fm.; Figures 12-42, Swan Hills Fm.)

Figure 1.	Plant? impression X2 (Location 16-31-61-11, 8490').
Figure 2.	Echinocaris? sp. spines X2 (Location 16-31-61-11, 8490').
Figure 3.	Conodont, ?Lonchodina? sp. X3 (Location 16-26-61-12, 8673').
Figures 4-7.	Bactrites sp. X2 (Location 16-26-61-12, 8687'). Longitudinal and cross-section views.
Figure 8.	Bellerophon sp. X20 (Location 16-5-62-11, 8601'). Cross sectional view.
Figure 9.	Pelecypod, ?Paracyclas? sp. X5 (Location 6-36-61-12, 8645').
Figure 10.	Crinoid stem X20 (Location 16-26-61-12, 8685'). Cross section of columnal.
Figure 11.	Tentaculites sp. X20 (Location 16-5-62-11, 8600').
Figure 12.	Ostracode X13 (Location 6-4-62-12, 8531'). Lateral view.
Figures 13, 14.	?Bythopora? s.l. X5 (Location 16-6-62-11, 8785'). Oblique and cross sectional views.
Figure 15.	cf. Cypricardinia sp. X2 (Location 16-6-62-11, 8793'). View of right valve of specimen.
Figures 16-18.	Nuculoidea? sp. X2 (Location 6-32-61-11, 8660'). Left lateral, dorsal, and anterior views.
Figures 19-21.	Echinocoelia ? sp. X2 (Location 16-6-62-11, 8793'). Left lateral, dorsal, and anterior views.
Figure 22.	Conocardium sp. X2 (Location 6-36-61-12, 8635'). View of one valve of specimen.
Figure 23.	Loxonema sp. X2 (Location 6-7-62-12, 8793'). Lateral view.
Figures 24-26.	?Murchisonia? sp X2 (Location 16-6-62-11, 8793'). Lateral views.

PLATE XIII - Continued

Figures 27,28. ? Strobeus? sp. X2 (Location 16-6-62-11, 8793'). Lateral views.

Figures 29-32. Bembexia sp. X2 (Location 16-6-62-11, 8793'). Lateral views.

Figures 33-36. Straparolus sp. X2 (Location 6-7-62-12, 9030'). Spiral and cross section views of specimens.

Figures 37, 38. Conocardium sp. X9 (Location 16-6-62-11, 8793'). Anterior and right lateral views.

Figure 39. Calcispheres X55 (Location 6-1-62-12, 9049'). Spined types.

Figure 40. Tikhinella sp. X55 (Location 16-5-62-12, 8620'). Cross sectional view.

Figures 41, 42. Foraminifera? cf. Parathurammina sp. X55 (Location 6-11-62-12, 8813').

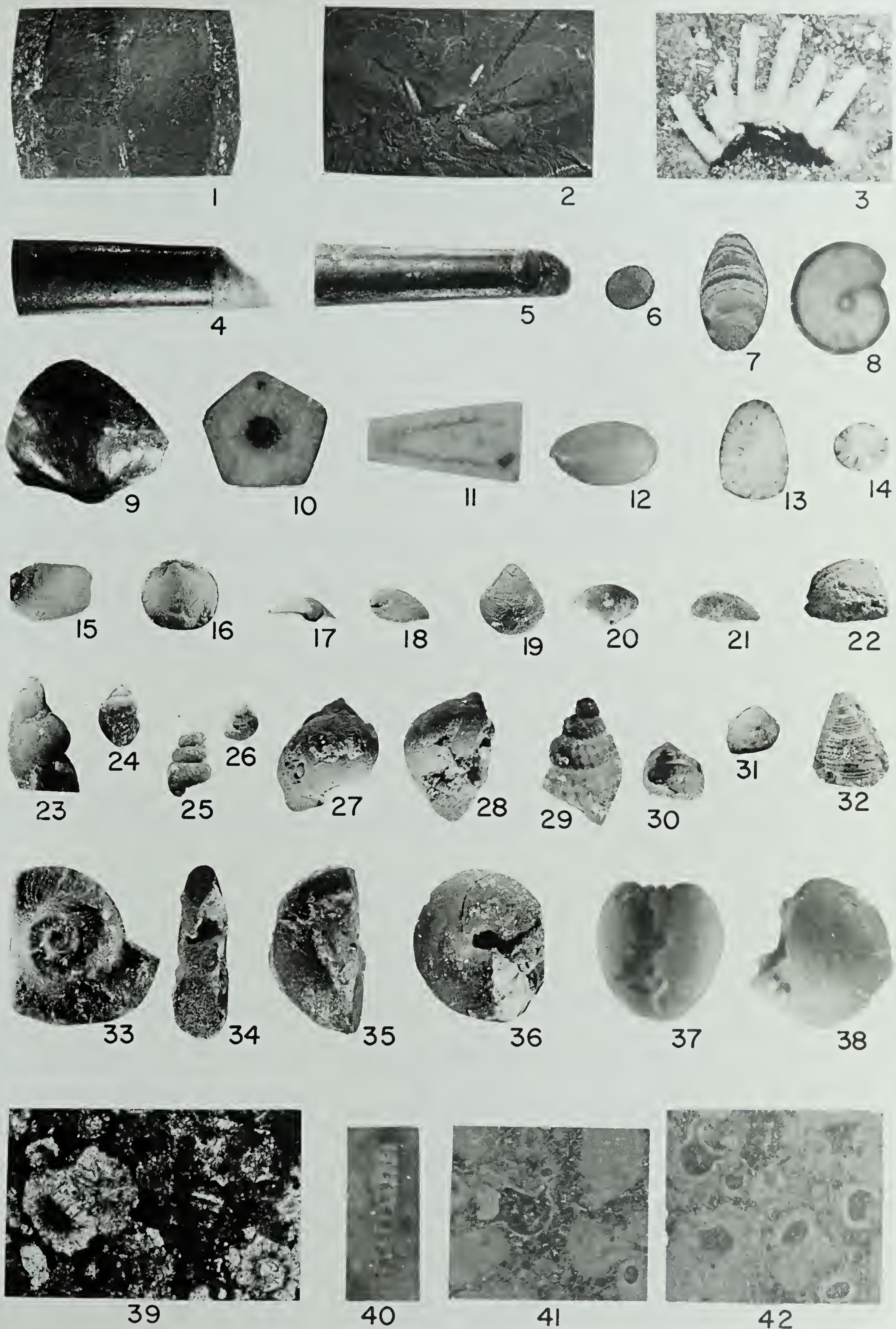
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PLATE XIII.

Tabulophyllum occur in rocks of the fore-reef facies. These corals are common in micritic sediments associated with tabular stromatoporoids and brachiopods and are believed to have favoured deeper and more quiet water than the tabulate colonial corals.

Brachiopods:

Brachiopods are very common in many of the rock types. A number of different genera have been identified and illustrated in Plates IX to XII, but few species identifications have been made because the number of good specimens that could be collected without damaging the core was small.

Inarticulate brachiopods characterized by *Lingula* occur in the argillaceous limestones of the Waterways Formation. Since present-day *Lingula* are found only on muddy bottoms in very shallow water, the water in which the limestones and shales of the Waterways Formation were deposited may not have been very deep.

Articulate brachiopods are abundant on the lower parts of the fore-reef slope; are common farther up the fore-reef slope, in the organic-reef facies and reef platform; but are rare to absent in most rocks of the back-reef facies. Complete specimens of *Atrypa*, *Schizophoria*, and other types characterize the lower fore-reef limestones. Single valves and fragments of such genera as *Atrypa*, *Cranaena*, *Stropheodonta*, and *Athyris*, etc., are common in the reef and upper fore-reef facies. *Eleutherokomma*, *Chonetes*, and *Atrypa* were recognized in the off-reef limestones of the Waterways Formation.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Brachiopods appear to have been able to adapt themselves to a wide variety of environments. Well-aerated water of normal salinity, however, seems to have been necessary, since brachiopods are rare in the back-reef area. The fore-reef and, to a lesser extent, the reef areas with moderately turbulent wave and current action were the most favourable environments for most of the brachiopods.

Pelecypods:

Pelecypods are rare and have been found only in the reef and reef-detritus limestones. Conocardium, the only well-represented pelecypod, can be recognized by its small, fragile shell with fine plicae, furrows, and growth lines, and by its characteristic shape and chalky white shell in hand specimen.

Though rare, pelecypods apparently favoured the shallow, turbulent, well-aerated water of the organic-reef and upper fore-reef. The easily recognizable Conocardium and its apparent restriction to the organic-reef and reef-detritus rocks suggest it may be an important environmental indicator.

Gastropods:

Gastropods occur in most of the rock types as scattered individuals. They are most abundant in some of the limestones of the back-reef and the deep fore-reef areas. Bellerophon and other small, discoid or spired gastropods are common in the micritic limestones of the Waterways Formation. Larger coiled and spired types identified as Loxonema, Straparolus, Bembexia, and Murchisonia have been found in the coarse limestones of the reef and fore-reef facies. Abundant, but

unidentified, large gastropods occur in the micritic limestones of the lower fore-reef associated with brachiopods and tabular stromatoporoids.

As pointed out by Klovan (1964) gastropods appear to have been ubiquitous and tolerant of a wide range of environments ranging from quiet to very rough water.

Crinoids:

Crinoid ossicles and rare echinoid spines occur in the reef and fore-reef limestones. In the back-reef limestones, crinoids are rare to absent. From the available evidence it is postulated here that crinoids grew in the more sheltered parts of the reef and in the relatively shallow, slightly agitated waters of the fore-reef slope. Though common in the micritic limestones of the fore-reef, no stems or heads were found intact. This suggests to the writer that these crinoid fragments were transported to the quiet-water environments, otherwise one would expect to find at least a few specimens partially complete. This interpretation is different from that of Klovan (1964) and Jenik (1965) who suggest that crinoids grew in a deep, quiet-water environment.

Ostracodes:

Though found in most rock types, ostracodes are most abundant and characteristic of the back-reef limestones. This agrees with most other Alberta reef studies but disagrees with Wolfenden's (1958, p. 886), Carboniferous reef study in England where he found ostracodes most common in the reef and fore-reef limestones. It is suggested

here that ostracodes probably favoured a quiet water, soft-bottomed environment, but their small, light shells were easily transported after death to all parts of the reef complex.

Bryozoans:

Bryozoan fragments are rare and were found only in the reef detritus. Fenestellid fragments and small, delicate, cylindrical forms tentatively assigned to the genus Bythopora? were found as scattered individuals in these high-energy deposits. Bryozoans are taken to indicate an open marine, agitated-water environment.

Foraminifera:

Numerous thin sections of the reef complex limestones contain minute spheres, globulose and irregular-shaped forms, many of which may be foraminifera. One characteristic type is very similar to and tentatively assigned to the genus Tikhinella (see Plate XIII, Figure 40). This is an Upper Devonian (Frasnian) foraminifera found in the Redwater reef and described by Toomy (1965). If the forms recognized here do belong to this genus, it would strengthen the Upper Devonian age assignment for the Swan Hills reef complexes.

Burrowing Organisms:

There is considerable evidence of burrowing activity in the off-reef and back-reef limestones. Though there is less evidence for boring in the limestones

of the reef and reef detritus, it probably occurred. Some burrows are filled with adjacent sediment whereas others are preserved as holes filled with secondary sparry calcite. The latter type of borings are believed to have been made in partially or wholly consolidated sediments.

Miscellaneous Fossils:

Those fossils found only in very small numbers or whose biological affinities are unknown are grouped together here.

Tentaculites is commonly found in the argillaceous limestones of the Waterways Formation and a few forms have been found in the reef-complex limestones. They are usually well preserved but occasionally are pyritized. They are believed to have been pelagic organisms.

Straight, orthoconic cephalopods occur sporadically in the micritic limestones of the Waterways Formation and outer fore-reef slopes of the reef complex. Those found have shells up to one and one half inches in length and one quarter of one inch in diameter. They are circular in cross section, have relatively complex septa, a thin outer shell, and a marginal siphuncle. They have been assigned to the genus Bactrites.

One small conodont fragment was found in the argillaceous limestones of the Waterways Formation.

Numerous chitinous fragments have been found especially in the Waterways Formation. One incomplete crustacean form, Echinocaris? was found.

Calcipheres which are very abundant in the Swan Hills carbonates are fossils of unknown affinity. They are very common in the back-reef limestones and are commonly associated with Amphipora, ostracodes, and Girvanella.

Algae:

Algae are the only evidence of plant life found in the reef complex. As pointed out by Edie (1961, p. 4) algae can assume a wide range of shapes and structures, but with the exception of calcareous algae leave little record of their presence in the rocks. Thus, the exact role played by algae in ancient reef complexes is not known. It is the writer's belief that algae were very important, especially in such roles as the trapping and cementing of sediment, and the corrosion and alteration of carbonate particles. Though direct evidence of algae is commonly lacking, indirect evidence of possible or probable algal activity is common throughout the rocks of the complex.

Parachaetetes and possible Solenopora? of the Family Solenoporaceae are the most easily recognizable and diagnostic algae found. (Plate XIV, Figures 1 and 2). Fragments and botryoidal clumps of these colonial red-algae are common in the fore-reef facies. If they were common in the organic-reef environment, the high energy conditions present there broke down and removed most of their delicate skeletons. On the fore-reef slopes, solenoporoid algae and tabular stromatoporoids form intergrown masses with brachiopods, corals, and crinoids that are interpreted to represent growing organic patch reefs. Much of the algal material is hard to recognize as it grades into and has been altered to micrite by grain-diminution (see

PLATE XIV

Algae and Algal Action

Figure 1. Solenoporoid algae. Polished section (reflected light) of the alga Solenopora? (possibly Parachaetetes) X40 (Location, 16-6-62-11, 8825').

Figure 2. Solenoporoid algae. Thin section of the alga Parachaetetes. Note the algal grain-diminution along the upper surface, X13 (Location, 16-6-62-11, 8828').

Figure 3. Oncolites. Hand specimen showing algal-coated stromatoporoid fragments, X0.7 (Location, 6-11-62-12, 8657').

Figure 4. Algal coated grains. Hand specimen showing Amphipora and other stromatoporoid fragments with a thin coating, X0.75 (Location, 16-6-62-11, 8840').

Figure 5. Algal filaments. Polished section (reflected light) of a possible algal structure showing numerous vertical filaments, X14 (Location, 16-5-62-12, 8598').

Figure 6. Algal corrosion. Polished section showing a stromatoporoid fragment coated and corroded by a micritic algal layer, X10 (Location, 6-11-62-12, 8698').

Figure 7. Algal mat. Hand specimen of a laminated micrite limestone. Laminations are believed to be algal-mat layers, X0.75 (Location, 6-36-61-12, 8549').

Figure 8. Algae? Thin section showing small spheroids that may be dasycladacian algae, X28 (Location, 16-6-62-11, 8791').

Figure 9. Girvanella. Thin section showing two clusters of Girvanella tubes mostly in contact and subparallel, X22 (Location, 16-5-62-11, 8642').

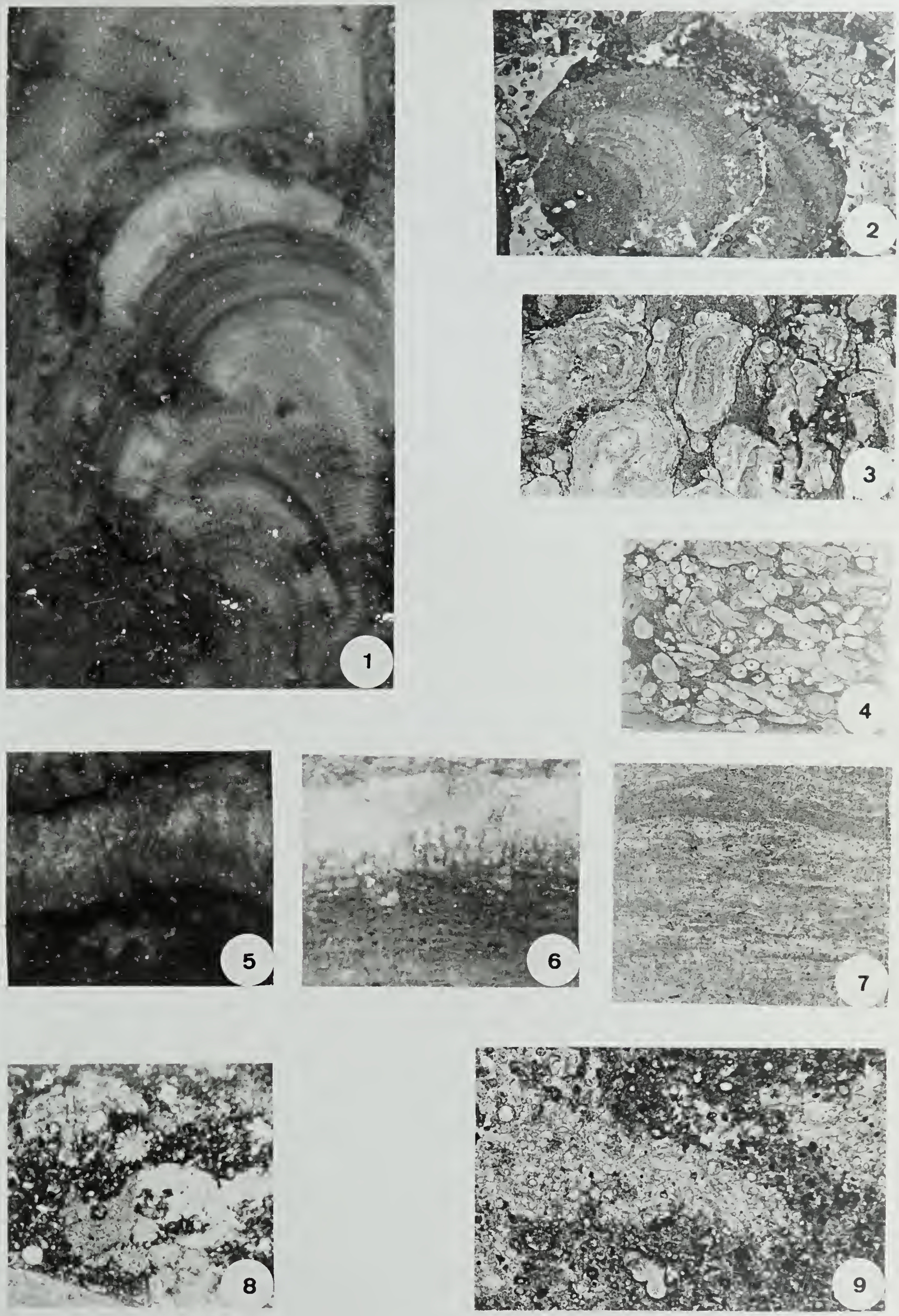


PLATE XIV.

Wolf, 1965).

Laminated coatings and encrustations are commonly observed enclosing allochems or grains (Plate XIV, Figures 3 and 4). Many of these coatings (the oncolites and algal coated grains) are interpreted as having been formed by algae, probably Spongiostromata. Though usually structureless, the mat-like layers occasionally show fine filaments or tubules suggesting an algal origin (Plate XIV, Figure 5). Besides coating the grains, these algae corrode and alter them as well (Plate XIV, Figure 6). Amphipora and other skeletal grains with micritic coatings can be seen in various states of alteration in many limestone samples.

Laminated limestones, common in certain back-reef areas, are also interpreted as being formed largely by algal mats (Plate XIV, Figure 7). These sediments closely resemble the present day intertidal and supratidal algal flats found in the Persian Gulf, the Bahamas, and the Florida Keys, etc.. Noncalcareous green or blue-green algae that were able to trap and bind sediment to form irregular layers are believed responsible for most of the laminated limestones found.

Colonies and isolated tubes assigned to the genus Girvanella are common in the back-reef areas (Plate XIV, Figure 9). These forms have been reported in most Devonian reef studies and appear to have favoured shallow, moderately agitated water. Other problematic forms (Plate XIV, Figure 8) occur which are possibly dasycladacean algae.

It is evident that algae were probably more important and widespread in the Carson Creek North reef complex than can be recognized by their preserved

record. Concerning their environment, it is evident that being plants and requiring sunlight, they could only thrive down to a certain water depth that varied with its clarity. The solenoporoid algae appear to have preferred the more open-marine reef and fore-reef environments while the green or blue-green algae preferred the more protected back-reef areas.

Fossil Distribution

For the purpose of illustrating the inferred life distribution of the various fossils, four facies are recognized: the off-reef or basin facies, the fore-reef facies, the reef facies, and the back-reef facies. Figure 10 is presented as a generalized distribution map of the fossils found in the Carson Creek North reef complex. The reef platform and western edge of the reef complex are not included in this diagram as there is inadequate paleontological information from these areas.

The dark, argillaceous basinal facies is characterized by inarticulate brachiopods, small articulate brachiopods, small gastropods, tentaculitids, and ostracodes. Both pelagic and benthonic forms are common in this facies.

The fore-reef limestones vary from micritic limestone to coarse reef-detritus. The fine-grained limestones of the lower fore-reef slope contain abundant brachiopods, tabular stromatoporoids, and large gastropods, with minor cup corals and crinoids. The coarse limestones of the upper fore-reef are characterized by Stachyodes, massive stromatoporoids, crinoids, and tabular corals, with algae, tabular stromatoporoids, bryozoans, and brachiopods common.

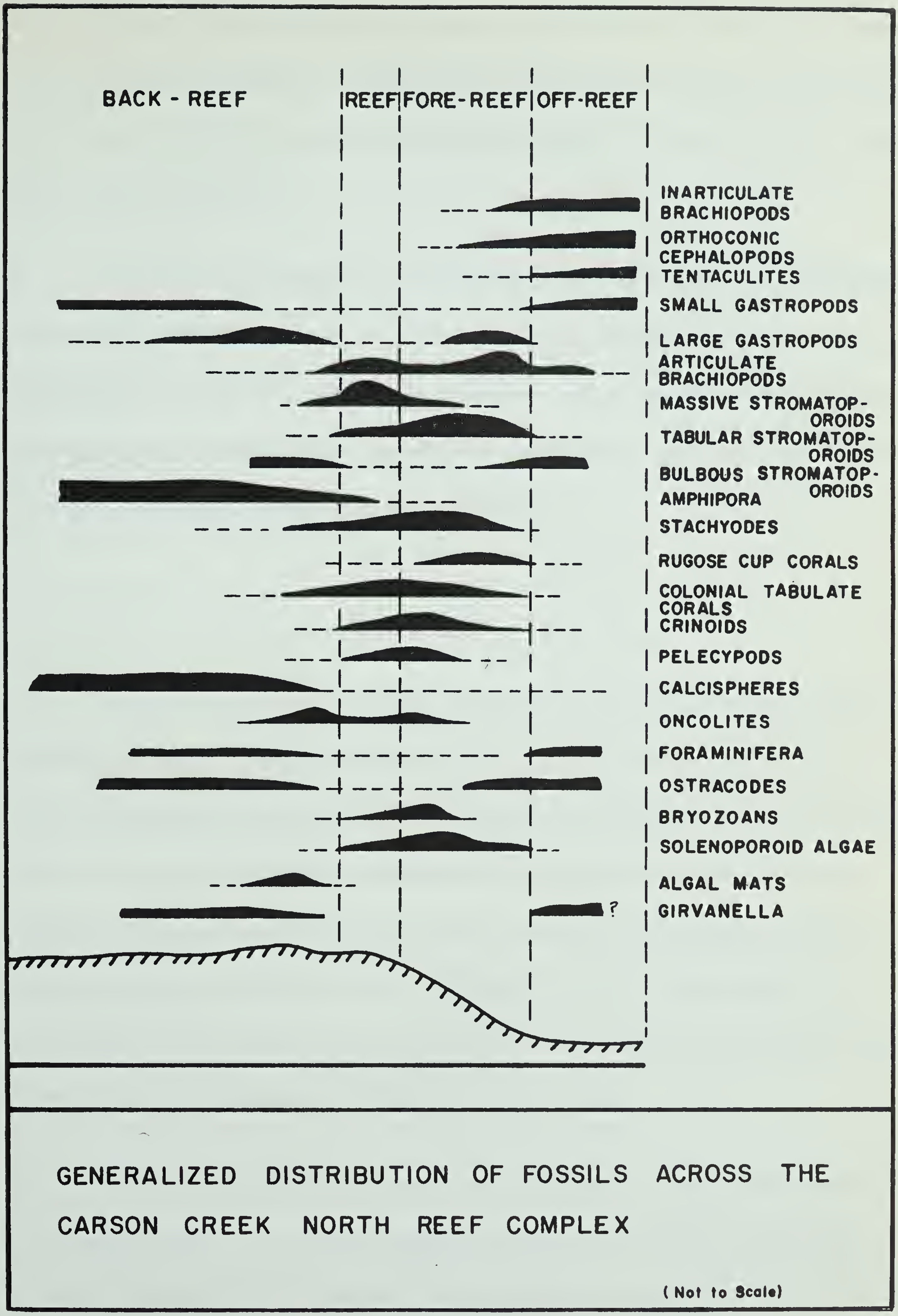


Figure 10. Generalized Distribution of Fossils across the Carson Creek North Reef Complex

The reef limestones consist of coarse skeletal debris and biolithites. Massive stromatoporoids are abundant; Stachyodes and tabular stromatoporoids common; and brachiopods, crinoids, pelecypods, solenoporoid algae, and corals are often present as scattered individuals.

The back-reef limestones are commonly micritic and pelletoid. Immediately leeward from the organic-reef, oncolites, Amphipora, massive stromatoporoids, and Stachyodes are important. In the more interior or central portions of the back-reef, Amphipora and calcispheres are the dominant skeletal constituents with varying amounts of algae, ostracodes, gastropods, and foraminifera.

Paleoecology

Since an environment is a subjective entity resulting from a large number of mutually interacting conditions and factors, there is no direct means by which it can be interpreted or portrayed. These interacting environmental factors, however, influence and are reflected by, the sediments and organisms present. Thus, by carefully studying the rocks and their fossils many of the environmental conditions that prevailed in an area can often be inferred. The relative water depth and turbulence, and to a lesser extent water salinity, clarity, and the character of the bottom, are the environmental conditions sought after here.

In this study seven distinct organic assemblages are recognized in the rocks of the reef complex. These assemblages are referred to as biosomes, defined by Wheeler (1958, p. 65) as, "mutually intertongued biostratigraphic units", and are designated by the most characteristic fossil or fossils present. Besides having dis-

PLATE XV

Reef Platform and Back-Reef Rock Types
(Hand specimens, with centimeter scale)

Figure 1. Dark brown, Amphipora micritic microfacies. Note Euryamphipora at top of photograph (Location, 16-5-62-11, 8647').

Figure 2. Dark brown, Amphipora micrite microfacies. Note how the Amphipora stems and laminae bend around the large lithoclasts (Location, 16-5-62-11, 8632').

Figure 3. Amphipora biomicrite. Numerous Amphipora in a dark calcarenitic matrix. Amphipora microfacies (Location, 16-5-62-11, 8617').

Figure 4. Light to medium brown, Amphipora intrapelmicrite. Amphipora microfacies (Location, 16-5-62-11, 8614').

Figure 5. Dark yellowish brown, Amphipora intrapelmicrite. Amphipora microfacies. (Location, 6-32-61-11, 8714').

Figure 6. Amphipora intrasparite. Amphipora microfacies (Location, 16-5-62-11, 8612').

Figure 7. Light brown, mottled, laminated intrapelmicrite. Dense, non-skeletal microfacies. Note laminated, fractured nature of rock (Location, 6-36-61-12, 8549').

Figure 8. Light brown, mottled, laminated intrapelmicrite. Dense, non-skeletal microfacies (Location 6-36-61-12, 8514').

Figure 9. Medium brown, sparry, mottled intramicrite. Dense, non-skeletal microfacies. Note how the mottling is related in part to the fracturing (Location, 16-5-62-11, 8619').

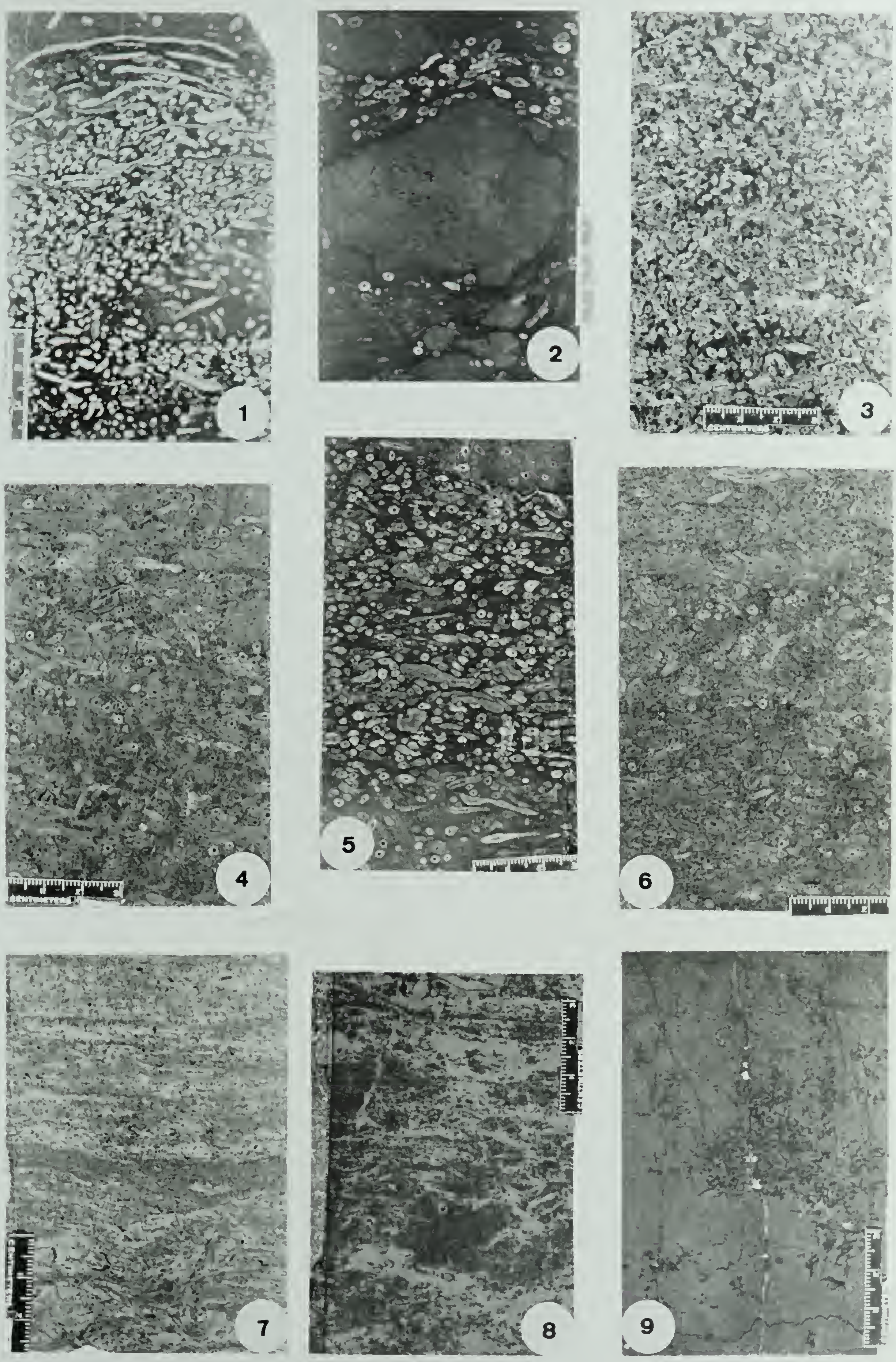


PLATE XV.

PLATE XVI

Back-Reef Rock Types
(Hand specimens, with centimeter scale)

Figure 1. Green shale. Green shale microfacies. Note the roiled or mottled character of the rock and the lack of fossils (Location, 6-11-62-12, 8864').

Figure 2. Green shale - laminated limestone. Green shale microfacies. Crenulated laminations are believed due to algal layers (Location 6-36-61-12, 8490').

Figure 3. Green shale - limestone breccia. Green shale microfacies. (Location, 6-36-61-12, 8492').

Figure 4. Porous, pellet limestone. Porous calcirudite microfacies. Note the lack of groundmass (Location, 16-6-62-11, 8696').

Figure 5. Amphipora calcirudite. Porous calcirudite microfacies. This rock is composed almost entirely of entangled Amphipora stems. (Location, 16-6-62-11, 8743').

Figure 6. Vuggy, stromatoporoid calcirudite. Porous calcirudite microfacies. (Location, 16-6-62-11, 8622').

Figure 7. Cream to light grey, bored, micritic limestone. Laminated - bored microfacies. Note the dense micritic character of the rock (Location, 6-4-62-12, 8547').

Figure 8. Laminated, sparry intrapelmicrite. Laminated - bored microfacies. Laminations believed largely due to algal mats (Location, 16-6-62-11, 8740').

Figure 9. Bored, laminated pelsparite. Laminated - bored microfacies. This rock type is very similar in appearance to recently formed beachrock. (Location, 16-6-62-11, 8724').

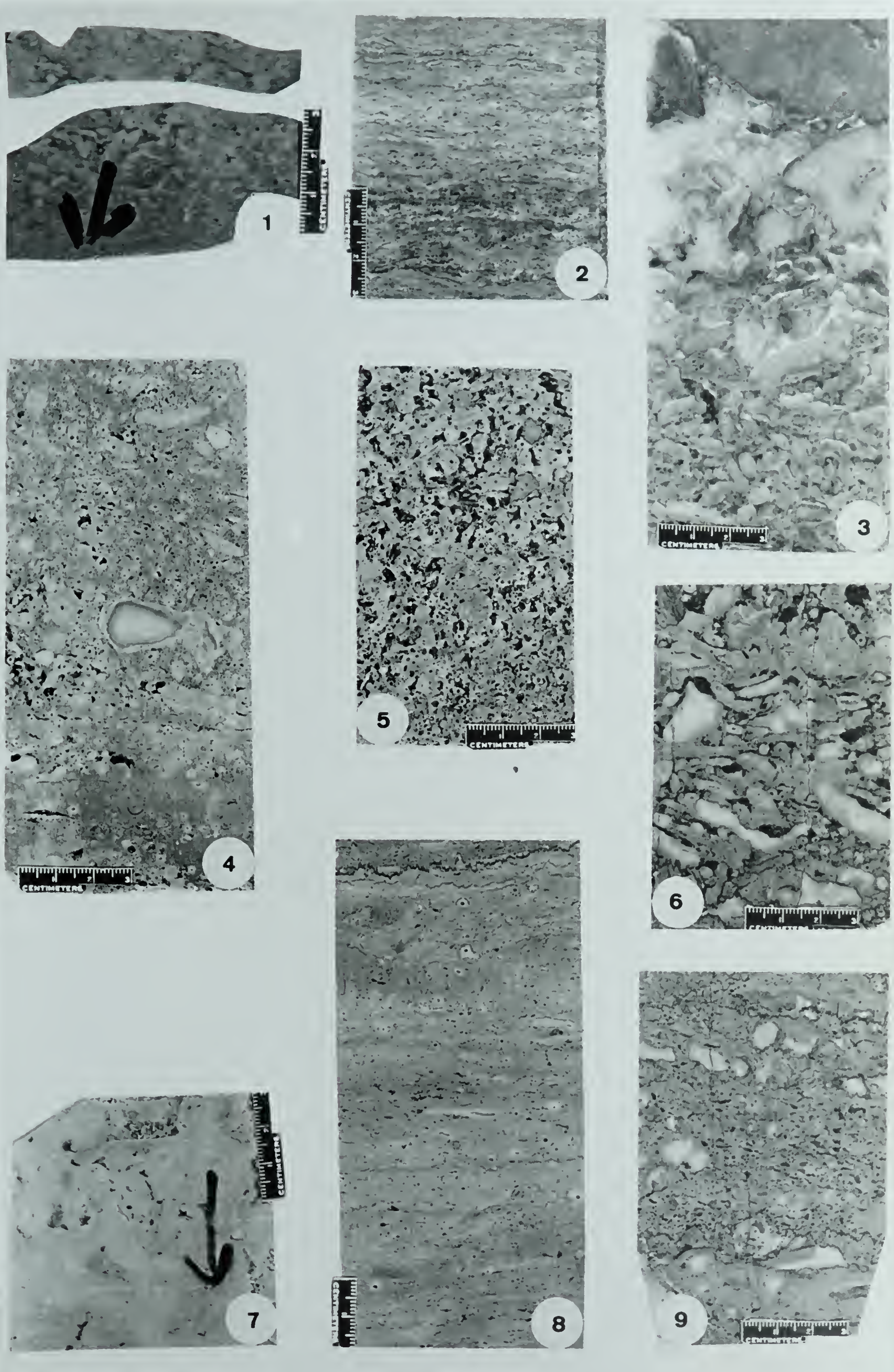


PLATE XVI.

PLATE XVII

Reef Detritus and Reef Rock Types
(Hand specimens, with centimeters scale)

Figure 1. Stromatoporoid biomicrite. Reef - flat, detrital microfacies. Various types of stromatoporoid fragments in a calcarenitic groundmass (Location, 16-6-62-11, 8692').

Figure 2. Massive stromatoporoid biomicrite. Reef - flat, detrital microfacies (Location, 6-11-62-12, 8657').

Figure 3. Oncolite biopelsparite. Reef -flat, detrital microfacies (Location, 6-11-62-12, 8657').

Figure 4. Skeletal calcarenite. Reef-flat, detrital microfacies. Note the coarse, even-grained nature of this rock (Location, 16-31-61-11, 8544').

Figure 5. Stromatoporoid biolithite. Massive stromatoporoid microfacies. Massive stromatoporoids enclosing other fossils and pockets of skeletal debris. (Location, 6-1-62-12, 8937').

Figure 6. Stromatoporoid reefoid limestone. Massive stromatoporoid microfacies. The rock consists largely of reef organisms (greater than 60%) that are beleived to have undergone only minor transport (Location, 16-6-62-11, 8754').

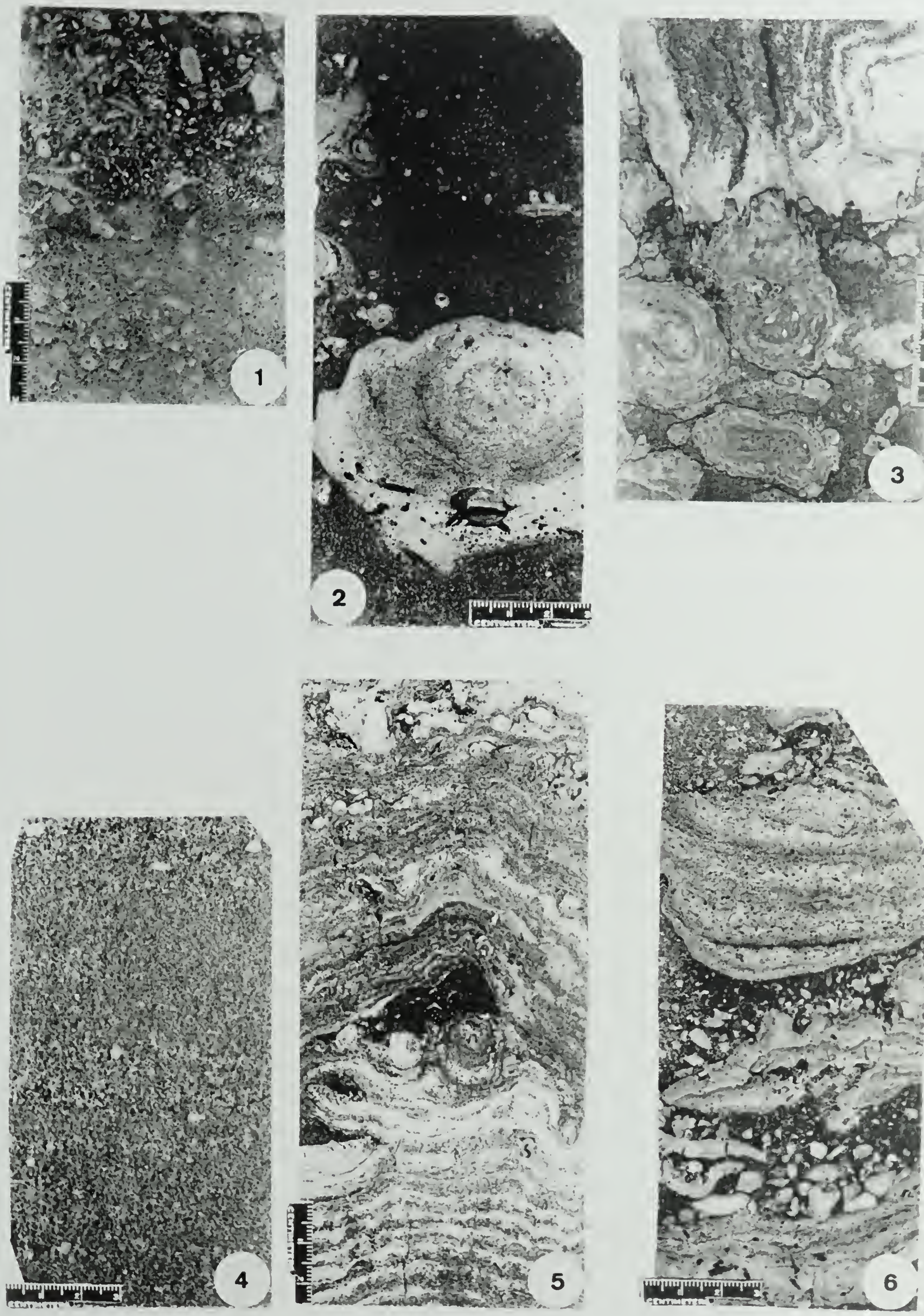


PLATE XVII.

PLATE XVIII

Fore-Reef and Off-Reef Rock Types
(Hand specimens with centimeter scale)

Figure 1. Coral-stromatoporoid biomicrite. Reef-flank, detrital microfacies. Coral and stromatoporoid fragments in a calcarenitic groundmass (Location, 16-31-61-11, 8540').

Figure 2. Stachyodes biomicrite. Reef-flank, detrital microfacies. The framework consists almost entirely of Stachyodes fragments (Location, 16-6-62-11, 8714').

Figure 3. Stachyodes-tabular stromatoporoid biopelmicrite. Reef-flank detrital microfacies (Location, 6-32-61-11, 8691').

Figure 4. Brown to grey, biopelmicrite. Reef-flank, detrital microfacies. Note flat brachiopod shells (Location, 6-32-61-11, 8675').

Figure 5. Tabular stromatoporoid-algal reefoid limestone. Brachiopod-tabular stromatoporoid microfacies. The groundmass consists largely of altered solenoporoid algae (Location, 16-6-62-11, 8792').

Figure 6. Stachyodes-tabular stromatoporoid, micritic limestone. Brachiopod-tabular stromatoporoid microfacies (Location, 6-36-61-12, 8621').

Figure 7. Dark brown, brachiopod-stromatoporoid biomicrite. Brachiopod-tabular stromatoporoid microfacies (Location, 16-6-62-11, 8811').

Figure 8. Reef-rubble limestone. Argillaceous limestone microfacies (Location, 6-7-62-12, 8996').

Figure 9. Argillaceous, nodular limestone. Argillaceous limestone microfacies. Note brecciated nature of this specific example (Location, 16-26-61-12, 8665').

Figure 10. Shaly, micritic limestone. Argillaceous limestone microfacies. Interbedded shale and argillaceous limestone layers (Location, 16-6-62-11, 8687').

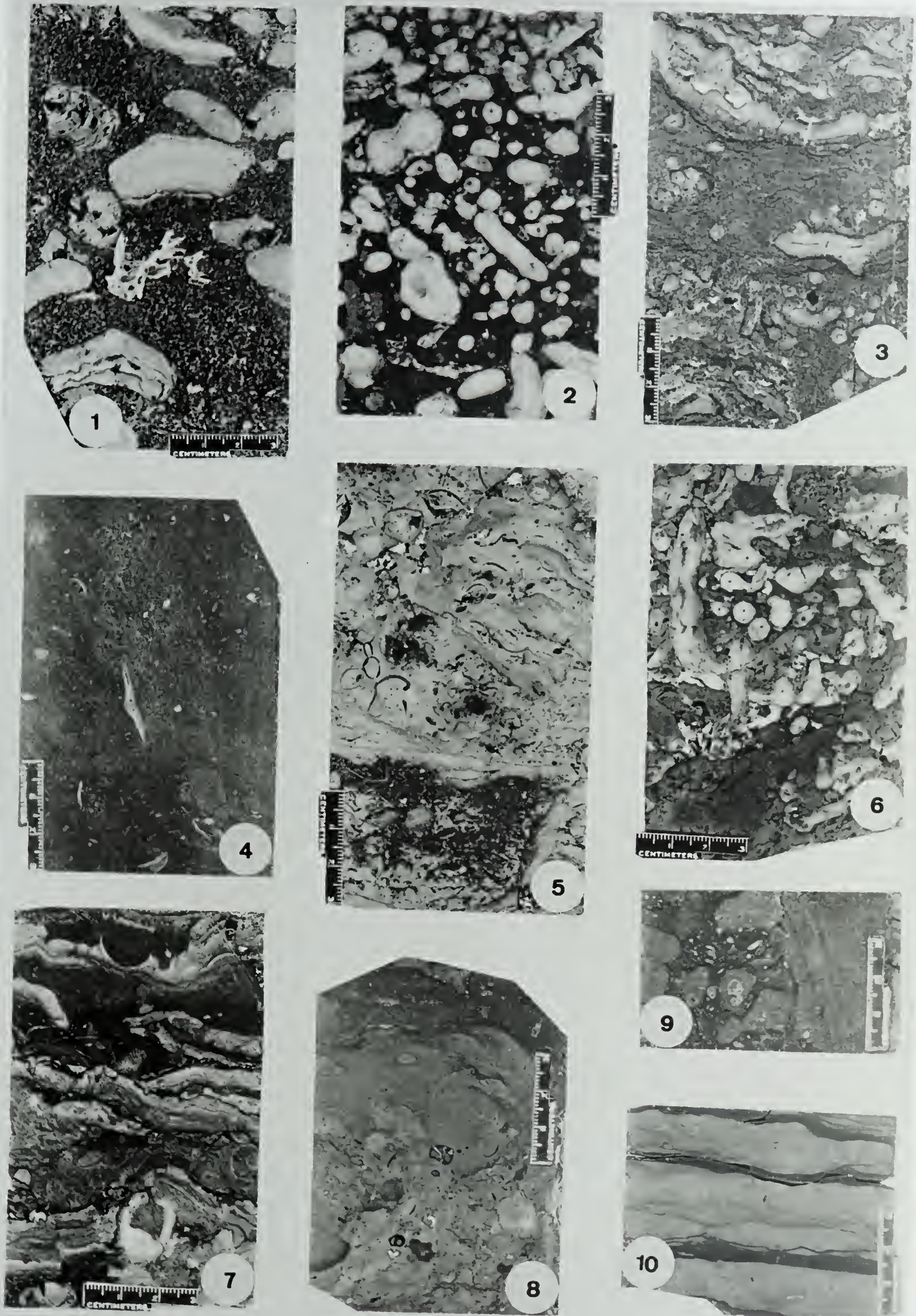


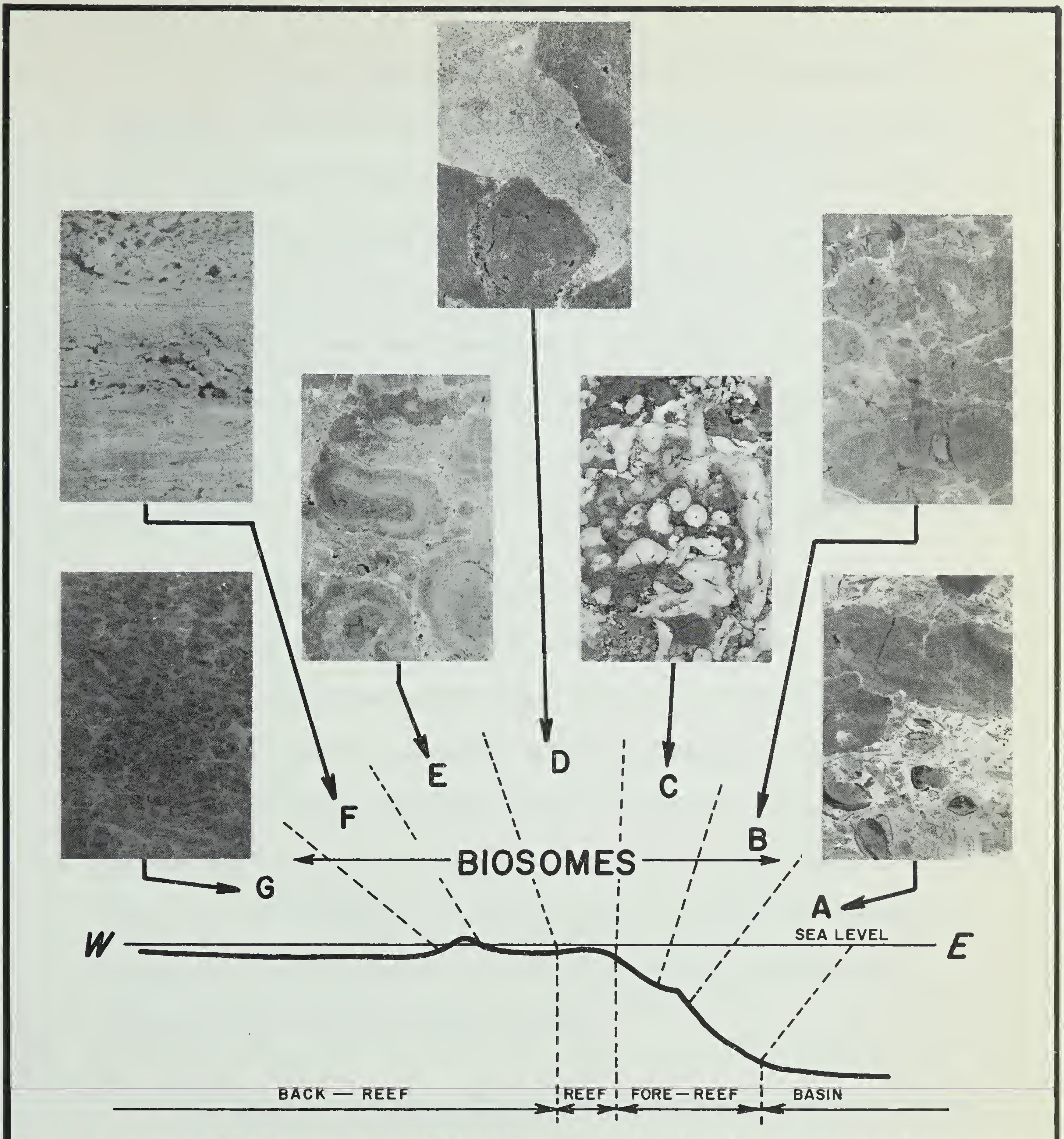
PLATE XVIII.

tinctive fossils, biosomes occur in characteristic lithologies as well, and are interpreted as representing areas of generalized uniform ecology (biotopes). The interpreted relative water depths and the most common geographic positions of the biosomes in the reef complex are presented in Figure 11.

Reef Complex Biosomes:

A. Brachiopod - Tabular Stromatoporoid Biosome - This unit is characterized by an abundance of brachiopods and tabular stromatoporoids many of which have intact shells and skeletons. Solitary cup corals, gastropods, and *Stachyodes* are commonly present as scattered individuals. Dark yellowish brown micritic limestone with patches of skeletal debris dominates the lithology. It is believed that this biosome represents the deepest and most seaward biotope of the complex. The bottom was probably soft and muddy and the overlying water relatively deep, calm, and not as well oxygenated as on most other parts of the complex.

B. Algal - Tabular Stromatoporoid Biosome - Solenoporoid algae, tabular stromatoporoids, and *Stachyodes*, many of which are in growth position, dominate this unit. Brachiopods and crinoids are also common. The principal lithology is light to medium yellowish brown micritic limestone, much of which is recrystallized solenoporoid algae. This unit is believed to represent in part, small, growing, organic patch reefs on the fore-reef slope. They probably grew in moderately deep and quiet waters. The light color and prolific organic growth indicates that the water was clear and well aerated by currents. The bottom was largely covered by growing reef organisms.



BIOSOME DISTRIBUTION

REEF COMPLEX BIOSOMES

A Brachiopod — Tabular Strom. Biosome
B Algal — Strom. Biosome
C Stachyodes Biosome
D Massive Strom. Biosome
E Oncolite — Amphipora Biosome
F Algal Mat — Bored Biosome
G Amphipora Biosome

Figure 11. Biosome Distribution Map, Carson Creek North Reef Complex

C. Stachyodes Biosome - This biosome is dominated by the presence of Stachyodes. Crinoids and tabulate corals are common along with minor amounts of massive stromatoporoids, brachiopods, solenoporoid algae, and pelecypods. The rocks are dominantly calcarenites though finer-grained micritic limestones are found. Most areas represented by this unit were subjected to considerable wave and current action with only isolated more protected areas. This unit occurs on the upper portions of the fore-reef slope and besides its indigenous fauna of Stachyodes, and Thamnopora, etc., it contains considerable detritus eroded from the organic-reef facies. Shallow, clear, normal marine waters characterized this fore-reef location.

D. Massive Stromatoporoid Biosome - Massive stromatoporoids both in growth position and, as reef detritus, are the diagnostic fossils of this unit. Crinoids and reef phase brachiopods, solenoporoid algae, and corals are found but not to the same extent as in the fore-reef facies. Pelecypods, gastropods, and Amphipora are rare. Consisting largely of biolithites and reefoid limestones, the rocks of this biosome represent shallow, turbulent-water conditions. The water must also have been clear, well oxygenated, and of normal salinity. The bottom was covered by lush gardens of growing reef organisms with patches of clean, relatively coarse, skeletal debris containing little organic growth.

E. Oncolite - Amphipora Biosome - Fragmented and rounded massive stromatoporoids, many covered by micritic or algal layers (oncolites), and Amphipora fragments characterize this biosome. Stachyodes, Thamnopora, and brachiopods are also common. Most of the material is reef-derived and few organisms are in growth position. This biosome is believed representative of the back-reef detritus

and dead reef-flat occurring immediately behind the organic-reef zone. Shallow, moderately turbulent water of normal salinity is envisaged for this environment. Though protected somewhat by the organic-reef, this area was swept by the incoming waves and currents.

F. Algal Mat - Bored Biosome - This biosome tends to be characterized by its lack of fossils with the exception of laminations which are believed to have been caused by algal mats, and sparry calcite "eyes" which are believed to represent organic burrows. Calcispheres, gastropods, and ostracodes are occasionally found and pellets are abundant. The character of the rocks in this biosome and their association with features attributable to subaerial exposure suggests an intertidal to supratidal environment. This agrees with the environment of modern sediments having a similar appearance, and their organic community. This biosome is taken to represent very shallow, restricted, saline waters occurring on and around small islands and banks in the back-reef environment.

G. Amphipora Biosome - This biostratigraphic unit is found throughout most of the central or back-reef portions of the reef complex and is characterized by an abundance of *Amphipora* stems and little else. Calcispheres are usually abundant, while ostracodes and small gastropods are common. The small size and nature of these forms and the scarcity of apparently stenohaline forms such as corals, echinoderms, and brachiopods suggests shallow, slightly restricted waters with above normal salinity. The environment probably corresponds to that found in many lagoons and protected shelf areas on modern reefs and banks.

CHAPTER 6 - FACIES ANALYSIS

Introduction

From the integrated data of the petrographic and paleontologic study, the rocks of the Carson Creek North reef complex have been divided into facies, microfacies, and rock types. These units are used informally for the purpose of reconstructing the original sedimentation patterns and environmental conditions of the reef complex. Though the individual rock types are descriptive, being based on distinctive lithologies and fossils, their grouping into microfacies and facies is genetic, resulting from inferred environmental similarities. These generalized genetic inferences enable one to portray the specific geomorphic depositional environments on cross sections or facies maps. Figures 12 and 13 illustrate the microfacies found in 3 cross sections constructed through the Carson Creek North reef complex.

In this study the Light Brown Member of the Swan Hills Formation has been divided into 3 facies, 9 microfacies, and 29 rock types. The Dark Brown Member of the Swan Hills Formation is regarded here as one microfacies and no rock types are differentiated within it. The Waterways Formation is also considered as one microfacies in which 3 rock types are recognized. The facies and microfacies recognized are summarized in Table 5, and briefly described and interpreted in the following pages. Figure 14 portrays the physiographic zones most commonly occupied by the various microfacies and facies and contains photographs of rock types that are characteristic of each environment.

Table 5. - Facies Classification of the Carson Creek North Reef Complex

FACIES	MICROFACIES	INFERRED ENVIRONMENT
(A) REEF PLATFORM FACIES	(a) Dark Brown, Amphipora Micritic Microfacies	Shallow shoal or platform with local variations in water depth and energy.
(B) BACK-REEF FACIES	(b) Amphipora Microfacies	Shallow to moderately deep, protected shelf or platform.
	(c) Dense, Non-skeletal Microfacies	Shallow, restricted, quiet-water on a lagoonal platform.
	(d) Green Shale Microfacies	Deposits formed largely by erosion and solution when portions of the reef complex were subaerially exposed for considerable periods of time.
	(e) Porous, Calcirudite Microfacies	Beach and strand line deposits forming low-lying islands and bars.
	(f) Laminated, Bored Microfacies	Intertidal to supratidal deposits associated with bars and low-lying islands.
	(g) Reef-Flat, Detrital Microfacies	Shallow, moderately turbulent-water deposits forming on the leeward side of the organic-reef facies.
(C) REEF FACIES	(h) Massive Stromatoporoid Microfacies	Actively growing, wave-resistant, organic framework in shallow, turbulent water.
(D) FORE-REEF FACIES	(i) Reef-Flank, Detrital Microfacies	Largely reef-derived rubble accumulating in relatively shallow water on the fore-reef slopes.
	(j) Brachiopod, Tabular Stromatoporoid Microfacies	Quiet, deeper water than for microfacies (i) occurring on the outer or deep fore-reef slopes.
(E) OFF-REEF OR BASINAL FACIES	(k) Argillaceous Limestone Microfacies	Off-reef or inter-reef deep, quiet-water sediments.

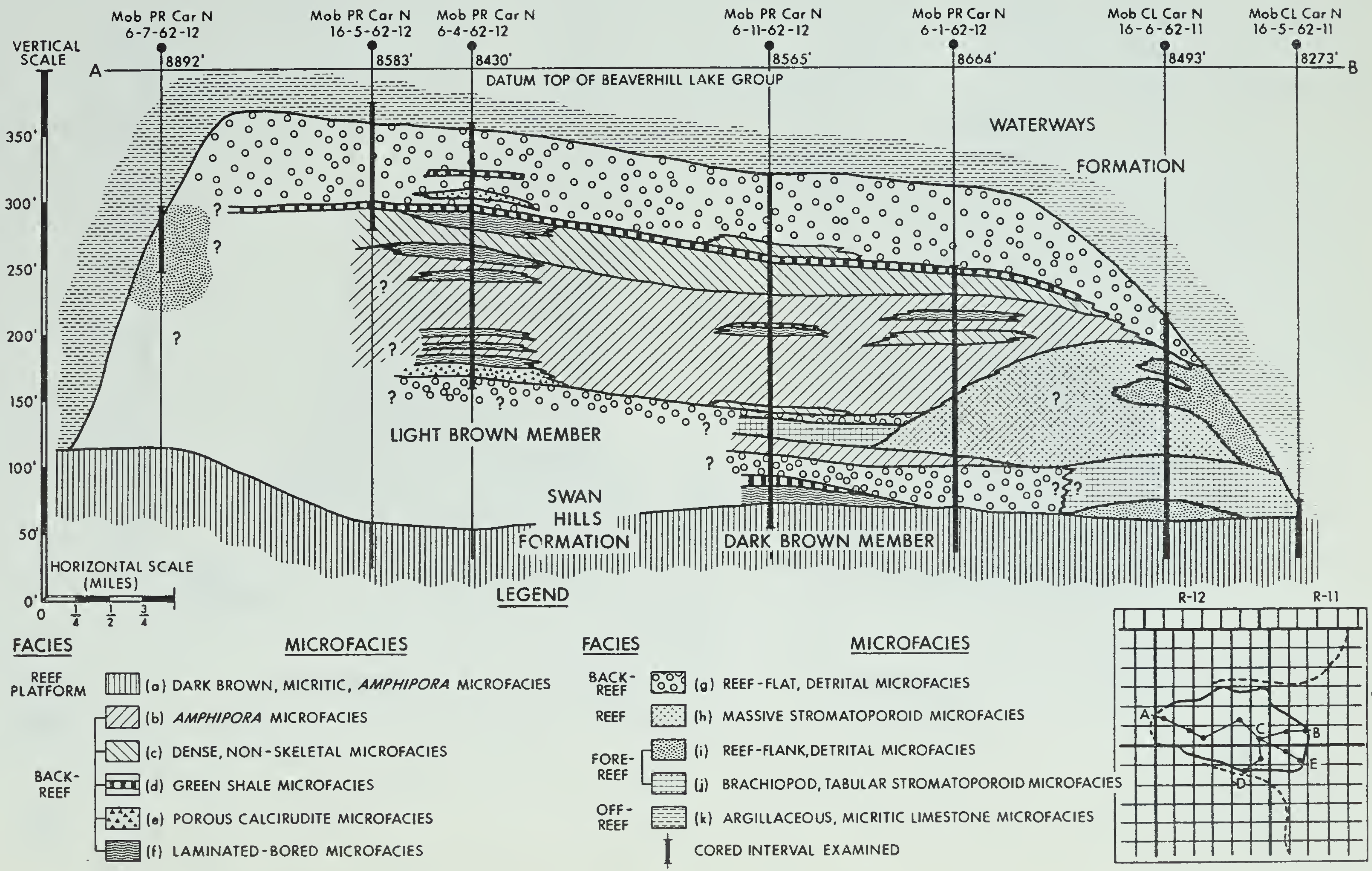


Figure 12. East – West Stratigraphic Cross Section of Carson Creek North Reef Complex Showing Facies and Microfacies Distribution

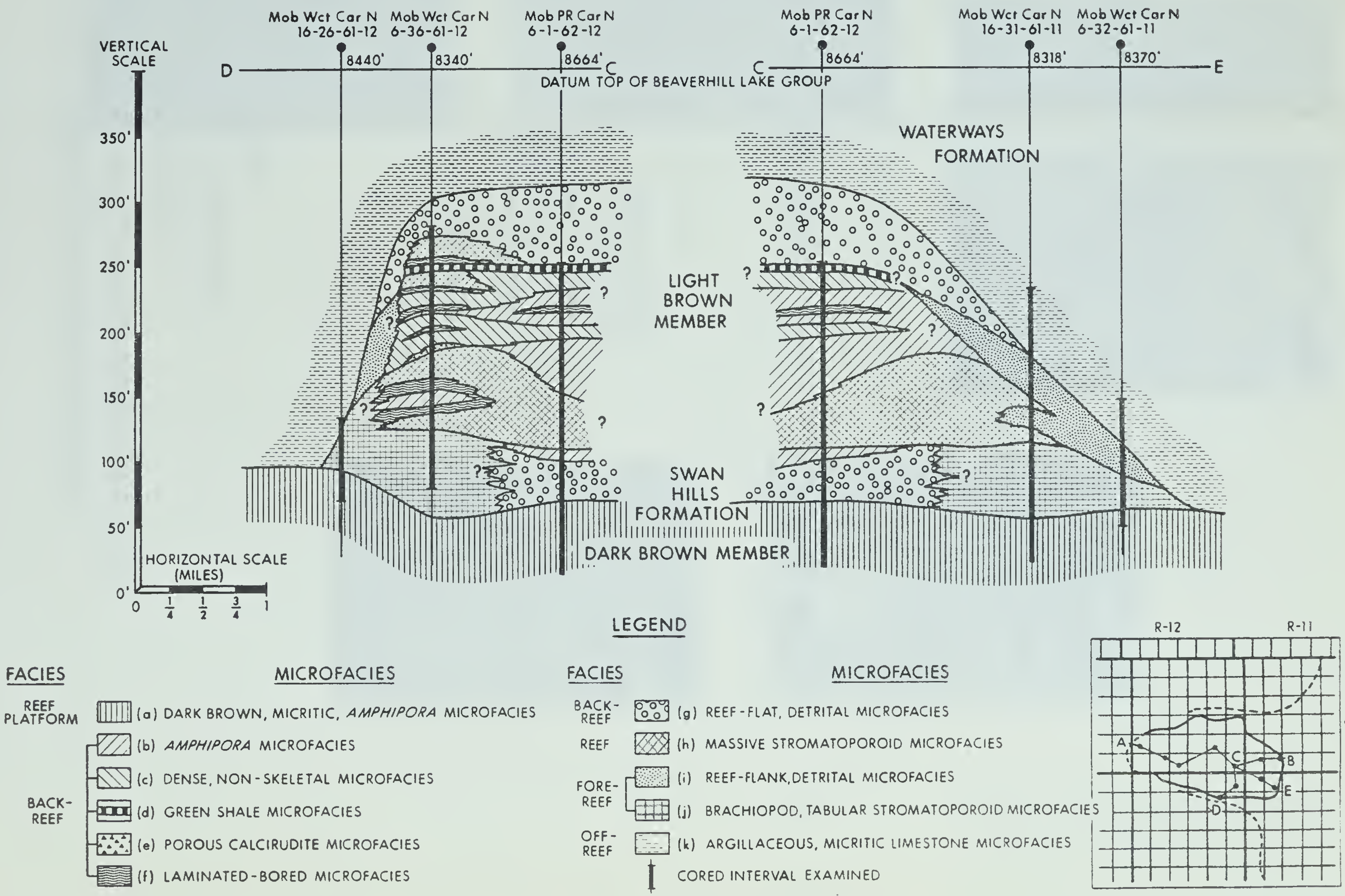
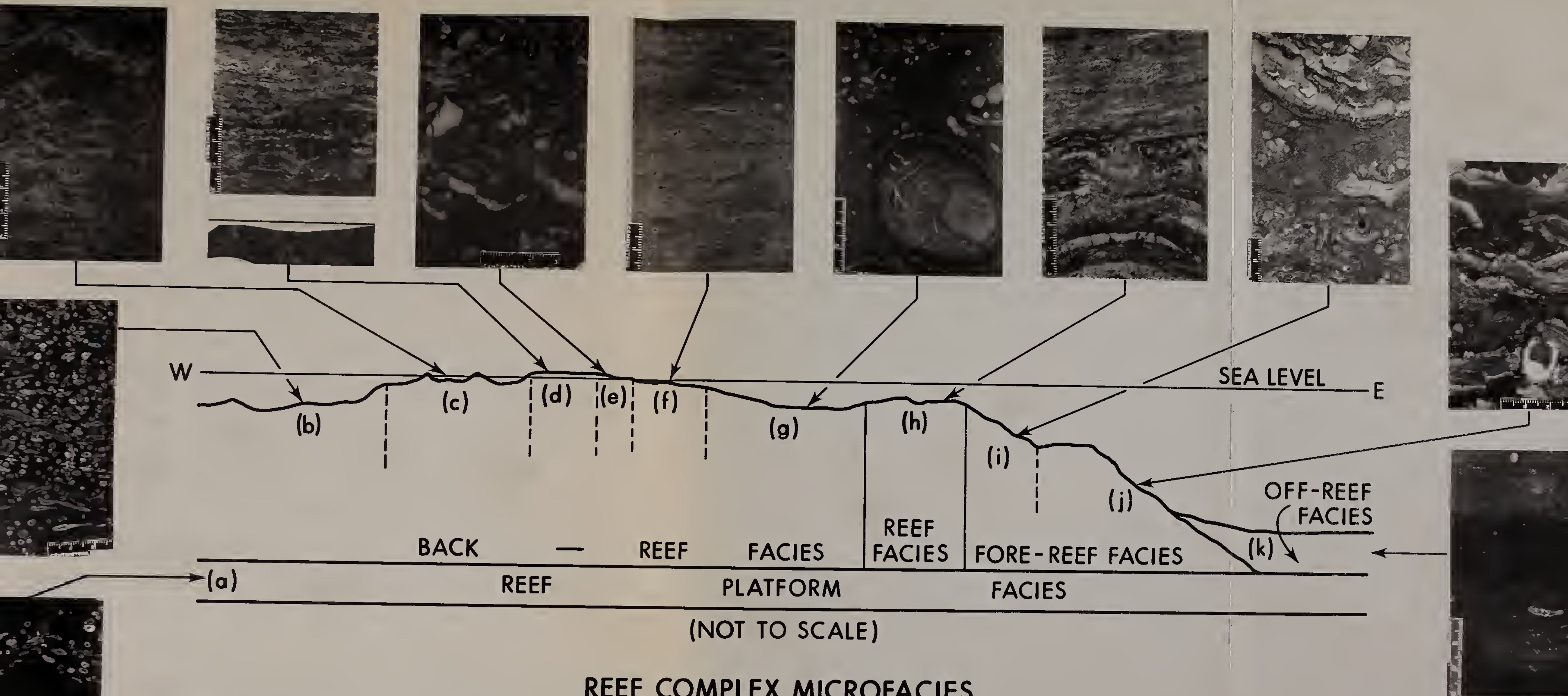


Figure 13. Stratigraphic sections in Southern and Eastern Sectors of Carson Creek North Reef Complex Showing Facies and Microfacies Distribution



REEF COMPLEX MICROFACIES

(a) DK. BRN., *AMPHIPORA*, MICRITIC MICROFACIES
(b) *AMPHIPORA* MICROFACIES
(c) DENSE, NON-SKELETAL MICROFACIES
(d) GREEN SHALE MICROFACIES
(e) POROUS CALCIRUDITE MICROFACIES
(f) LAMINATED, BORED MICROFACIES
(g) REEF-FLAT, DETRITAL MICROFACIES
(h) MASSIVE STROMATOPOROID MICROFACIES
(i) REEF-FLANK, DETRITAL MICROFACIES
(j) BRACHIOPOD, TABULAR STROMATOPOROID MICROFACIES
(k) ARGILLACEOUS, MICRITIC LIMESTONE MICROFACIES

Figure 14. Facies and Microfacies Distribution, Carson Creek North Reef Complex

Swan Hills Formation

(A) Reef Platform Facies:

The Dark Brown Member has received little detailed study here and the various lithologies are considered as one general microfacies. For detailed lithologic descriptions of the reef platform the reader is referred to Jenik (1965) and Murray (1966) who each recognize 12 platform rock-units.

Dark Brown Amphipora Micritic, Microfacies (a) (Plate XV, Figures 1 and 2).

The various units making up this microfacies are very similar to several of the back-reef types. They are usually, however, finer grained and darker in color. Though dark brown, dense limestones dominate the lithology, occasional beds of coarse, porous, light brown limestones are found. Amphipora dominates the fauna but bulbous stromatoporoids, corals, brachiopods, crinoids, ostracodes, and calcispheres are commonly present. One unit is characterized by abundant Thamnopora but it is neither as thick nor as distinctive as the so-called "Coral Bed" of the Swan Hills field (Fong, 1960).

The rocks of the platform are biostromal in character representing deposition on a broad, open-marine shelf. Their fine-grained nature and dark color, due to abundance of argillaceous and carbonaceous matter, indicates deposition in a low-energy environment. The isolated occurrences of abundant corals and stromatoporoids, sparites, and light-colored rocks, however, suggest local, shallow areas of higher energy.

(B) Back-Reef Facies:

The back-reef facies includes a number of microfacies and rock types that are interpreted to represent several distinct depositional environments. These back-reef sediments are usually darker in color than the reef sediments and lighter in color than those of the reef platform. They tend to be poorly bedded and subhorizontal. Non-skeletal grains predominate over skeletal, and micrite is common throughout. Much of the micrite is believed to represent sediment originally consisting of soft, pliable, pellets and grains that on compaction merged to form a dense, micritic-looking lithology.

The outer margin of the back-reef area immediately behind the organic-reef is made up largely of coarse skeletal debris and reef detritus. Fragmented reef-phase organisms are common here. Closely associated with this debris are rocks interpreted to represent deposition on and around low-lying islands and bars. Laminated and bored pelletoid sediments and calcirudites characterize the deposits of these environments. In the deeper areas between the islands and towards the centre of the back-reef platform, the rocks are characterized by darker colored, fine grained, pelletoid limestones containing abundant _Amphipora_.

It is believed the water covering the back-reef area was warm, quiet, and moderately shallow. Around the margins the water was shallower with stronger currents while toward the centre of the complex the water became deeper, calmer, and more restricted.

Amphipora Microfacies (b)

The rocks of this microfacies are widespread and are characteristic of the back-reef facies. Abundant Amphipora are diagnostic and give the microfacies its name. Both skeletal and non-skeletal grains occur, though the latter are the most abundant. Micrite predominates over spar. These rocks are characteristic of the central portions of the reef complex and are believed to represent deposition in deeper, more restricted waters.

The four rock types of the Amphipora microfacies recognized here are as follows:

(1) Amphipora Biomicrite (Plate XV, Figure 3). Commonly dark yellowish brown, though color varies, this rock type has a crude sort of bedding caused by the parallel alignment of Amphipora stems and stylolitic layers. Though generally dense, some intraskeletal and intergranular porosity is occasionally found in these rocks. The framework comprises 30-60 per cent of the rock and consists largely of Amphipora fragments. The Amphipora coenostea tend to be larger in size in the lighter-colored rocks but are much more abundant in the darker types. Ostracodes, gastropods, and calcispheres are common and bulbous stromatoporoids rare. Skeletal fragments (usually Amphipora) are the dominant grains but intraclasts are common. Pellets and coated grains occur locally. Micrite is much more important than sparry calcite in this unit, and is commonly silt-sized. Much of the micrite is believed to have formed by the corrosion and break down of skeletal fragments. Dolomite and pyrite occur as authigenic accessory minerals.

This rock type is believed to represent deposition in moderately deep water close to shallow shoals or banks. The large amounts of coarse skeletal debris and

intraclasts indicates the presence of shallow, current-swept areas nearby, while the abundance of micrite, Amphipora, and carbonaceous matter implies deeper, more protected waters at the actual site of deposition.

(2) Light to Medium Brown, Amphipora Intrapelmicrite (Plate XV, Figure 4). This rock type is characterized by its light color, abundance of Amphipora, and scarcity of skeletal constituent grains. The framework particles, composed almost entirely of Amphipora stems, usually make up 10-40 per cent of the whole rock. Massive stromatoporoid fragments, Stachyodes, and gastropods are rare. Grains, 30-60 per cent, consist of pellets and intraclasts, with skeletal grains in certain areas. Calcispheres and Girvanella are common. The grains often show moderate sorting, and intergranular pin-point porosity is occasionally present. Micrite is usually more plentiful than sparry calcite but occasionally the reverse is the case.

This rock type is commonly found towards the outer edges of the back-reef environment and is believed to represent deposition in relatively shallow, slightly agitated water of more or less normal salinity.

(3) Dark Yellowish Brown, Amphipora Intrapelmicrite (Plate XV, Figure 5). This rock type is very similar to the one just described, but it is darker in color, more micritic, and contains some argillaceous material. Amphipora stems are abundant and algal-coated grains and lithoclasts are common, while bulbous stromatoporoids and gastropods occur occasionally as framework constituents. Because of the dense nature of the rock, grains are hard to distinguish from true micrite. Intraclasts and coated grains are most common, but pellets are also plentiful; skeletal grains occur, but are rare. Though micrite and sparry calcite are present, the

former is by far the most plentiful. Fractures and stylolites are common, as is pyrite, especially along the stylolitic layers.

This rock type is inferred to represent deposition in moderately deep back-reef waters subjected to only gentle wave and current action. A few examples of very dark rocks indicate local areas of more stagnant or reducing conditions.

(4) Amphipora Intrasparite (Plate XV, Figure 6). Abundant Amphipora stems, intraclasts, and sparry calcite distinguish this rock type. The color varies from pale yellowish brown to dark yellowish brown and the rocks occasionally have a mottled appearance. The framework, constituting 50-70 per cent of the total rock, consists predominantly of Amphipora fragments but large micrite-coated lithoclasts and Stachyodes are common. Many of the framework particles are worn and rounded indicating considerable transportation or agitation. Grains, 15-30 per cent, largely intraclasts and pellets, tend to be subrounded and are often partially recrystallized to spar. Ostracodes are common while coated grains and superficial oölites may be present in minor amounts. Most of the grains are surrounded by sparry calcite, but micrite is usually present in lesser amounts. Pyrite is a very common accessory mineral and two isolated occurrences of chert were noted. Dolomite is rare in this rock type, as are stylolites.

These sediments appear to have been deposited in shallow water that was subjected to some agitation or wave action. They may represent deposition on shallow shoals or knolls in the central back-reef lagoon.

Dense, Non-Skeletal Microfacies (c)

The rocks of this unit are characterized by being generally light in color, very dense and micritic, and by consisting predominantly of non-skeletal grains. Amphipora are commonly present but usually make up less than 10 per cent of the total volume. These sediments often have a mottled appearance and may be highly fractured and bored. The rock types of this microfacies are commonly associated with, and grade into, those of the Amphipora microfacies (b) and those of the laminated-bored microfacies (f). The dense, non-skeletal rocks are believed to have been deposited in very shallow, restricted, lagoonal environments closely associated with islands or shoals.

The following two sediment types belong to this division:

(1) Light Brown, Mottled, Laminated Intrapelmicrite (Plate XV, Figures 7 and 8). The diagnostic features of this rock are its tan to light brown color, its mottled appearance, and its lack of skeletal constituents. The mottling is caused by the presence of darker areas that occur as irregular patches or layers in very light tan to cream-colored limestone. The darker areas are caused by a thin brown coating of organic matter or iron oxide on the grains. These areas are either associated with fractures, bedding planes, or more sparry areas. The mottling is therefore believed to be a diagenetic phenomenon closely connected with void space or channelways. Some of the mottling may also be due to burrowing or organic activity. Framework constituents are scarce, usually less than 10 per cent, and consist of a few scattered Amphipora, Stachyodes, and bulbous stromatoporoid fragments. Grains are abundant, 40-65 per cent, consisting largely of intraclasts and pellets. The groundmass is

predominantly micritic though sparry calcite is common as infill. Pyrite and calcispheres are common accessories. Very often these sediments show fine laminations which on occasion have graded bedding and structures resembling small-scale cross-stratification.

A very shallow, yet quiet-water environment is postulated for this rock type. The paucity of fauna suggests a restricted, lagoon-like environment of increased salinity.

(2) Medium Brown, Sparry, Mottled Intramicrite (Plate XV, Figure 9). In hand specimen, this sediment type appears to be a calcilutite or micritic limestone, but microscopic examination shows that it is largely composed of tightly packed intraclasts and pellets. The rock is often mottled and fractured with the two features being closely associated. The color is usually medium to dark yellowish brown. The proportion of framework particles is small, 0-30 per cent, with Amphipora being the most common constituent. Lithoclasts, oncolites, and gastropods are rare. Grains make up the bulk of the rock, 40-65 per cent, but micrite can comprise up to 50 per cent in some cases; closely packed intraclasts, pellets, and calcispheres are the principal types. Spar is not common except as infill in vugs and borings which are abundant locally.

This rock type is closely associated with the light brown, mottled, laminated intrapelmicrite previously described, and is believed to represent a similar environment. The darker color may be due to more stagnant conditions caused by the water being either deeper or more quiet, or both.

Green Shale Microfacies (d)

The green shale microfacies is characterized by the presence of light green, slightly calcareous shale. This argillaceous material is most commonly found either as laminated shale beds, as irregular lenses or laminae associated with laminated limestones, or as inclusions, vug filling, and matrix associated with limestone breccias and light grey micritic limestones. The most important occurrence of this unit is in the so-called "green-shale marker" which is located approximately 50 feet below the top of the central portion of the reef complex. In this marker the shale microfacies reaches thicknesses up to 20 feet and can be traced laterally over most of the complex. Thinner, discontinuous shale zones can be found locally at various depths throughout the back-reef limestones.

The green shale sediments are believed to have formed when much of the reef complex was above sea level for a considerable length of time. The sediments themselves are interpreted to largely represent residues left after considerable solution and erosion of the reef carbonates, and in part to be shallow-water deposits formed in pools and lagoons on the exposed reef surface.

Among the interesting assemblage of limestones associated with the green shale the following three rock types are recognized:

(1) Green shale (Plate XVI, Figure 1). The green shale has a laminated to nodular appearance, is non-fossiliferous, pyritic, and contains abundant lenses and lithoclasts of micritic limestone. Murray (1966), states that the green shale consists mineralogically of illite, pyrite, rare chlorite, quartz, and dolomite. The maximum thickness of green shale found was about one foot, but much of it is believed to have

been lost during coring.

The green shale found within the reef-complex limestones is considered here to be largely internal sediment or insoluble residue left during solution of carbonate rock. Some of the clays, however, may represent precipitates formed in the reef-complex environment under special conditions. The thick and continuous "green-shale marker" is believed to represent a long time interval during which a considerable portion of the reef complex was uplifted and eroded.

An alternative explanation for the green shale is that it represents land-derived clays that settled on the reef complex after being carried there in suspension from the off-reef environment by an unusually long and violent storm (Edie, 1966, personal communication). This explanation, though attractive, is not favoured here because of the appreciable thickness of the shale unit, the presence of what are believed to be solution breccias, and the lack of coarse reef-organism fragments that one would expect to be interbedded with the shale if it was caused by prolonged hurricane or violent storm activity.

A third possible origin for the green shale beds is that they are the result of clays settling on the reef complex during subsidence or a deepening of the overlying waters. The reasons for believing that the shale represents uplift and erosion rather than such deep-water argillaceous sedimentation are as follows:

(1) The distinctive difference in color, mineralogy, chemistry, and general appearance between the green shale and the off-reef, dark, marine shales.

(2) The lack of any deep-water sediments immediately above or below the green shale beds.

(3) The abundance of breccias and algal-laminated limestones associated with the green shale beds.

(4) No fossils were found in the green shale.

(2) Green Shale-Laminated Limestone (Plate XVI, Figure 2). Discontinuous, crenulated laminations interbedded with green shale layers characterize this rock type. The laminations are very distinct and are believed to have originally been algal mats laid down in a supratidal environment. Macrofossils are absent but calcispheres, burrows, and pellets are found. The pellets, calcispheres, and lime mud have an agglutinated appearance and may represent material blown or washed into this environment during storms to be trapped by the mucilaginous nature of the algal mats. Sparry calcite is common as irregular layers between the laminae, while pyrite and reddish iron oxide (?) films are the only other accessories found.

These green shale - laminated limestones are believed to have been deposited in supratidal and intertidal environments found along the outer shores or inner embayments of large uplifted portions of the reef complex.

(3) Green Shale - Limestone Breccia (Plate XVI, Figure 3). Two closely associated yet slightly different breccias are grouped together within this rock type. One is a nodular to slightly brecciated, cream to light grey micritic limestone that has numerous green shale partings and matrix between the fragments. Pellets and micrite are the dominant constituents of this limestone while calcispheres, ostracodes, and rare stromatoporoid fragments are the principal fossils. This breccia is believed to have formed in shallow, isolated, saline pools on broad subaerial portions of the

reef complex. The ripping-up and brecciation of the semiconsolidated lime muds by waves and currents, together with the deposition of the green clays into these ponds from the surrounding exposed areas could account for this rock type.

The second type of breccia consists of large, angular lithoclasts and framework fossils loosely packed in a sparry calcite matrix. The sparry calcite infill is very abundant making up 40 to 50 per cent of the rock in places. Corals, Stachyodes, massive stromatoporoids, and Amphipora fragments, often as part of large lithoclasts, are the principal framework constituents. Besides the abundant sparry calcite; green shale partings, white milky calcite, and red iron oxide (?) occurs lining or coating the fragments.

This unit is interpreted to be a subaerial solution breccia. It is believed that most of the finer carbonate matrix was dissolved or leached away leaving a coarse, angular, loosely packed breccia of the more resistant fossil fragments. The large interstices between fragments were then lined with thin layers of fibrous calcite, green shale, and red iron oxide before burial. After burial the vugs were completely filled with coarse sparry calcite. Though the above interpretation is favoured the possibility of this breccia being a water transported, clastic deposit cannot be discarded.

Porous Calcirudite Microfacies (e)

Grain-supported rocks composed largely of broken and rounded framework constituents with little or no mud make up this rock unit. The fragments are cemented with sparry calcite but these rocks have good intergranular porosity. These

sediments may represent coarse materials that were transported by waves and currents to beaches or strand lines where they were deposited. They may also represent winnowed deposits that have undergone little or no transportation. The first possibility is favoured here because of the highly fragmented, abraded, and sorted nature of the particles.

Three closely related rock types have been grouped to make up this microfacies:

(1) Porous, Pellet Limestone (Plate XVI, Figure 4). Well rounded and moderately sorted grains and framework constituents, excellent intergranular and intraskeletal porosity, lack of lime mud and little spar, are the features that characterize this grain-supported sediment. Framework constituents (20-40 per cent) consist largely of *Amphipora* fragments with lesser amounts of *Stachyodes* and lithoclasts. Pellets dominate the grains (30-60 per cent) with intraclasts and coated grains being present in varying amounts. Thin interbeds and lenses are commonly composed almost entirely of well sorted and rounded pellets. Locally these sediments are laminated and grade into the laminated pelsparites.

This rock type is interpreted to represent either intertidal shoal or bar deposits, or beach deposits.

(2) *Amphipora* Calcirudite (Plate XVI, Figure 5). This is a very porous, light brown limestone made up almost entirely of entangled *Amphipora* stems and fragments. Groundmass is rare though sparry calcite occasionally fills up the interskeletal spaces. The framework (50-60 per cent) consists largely of *Amphipora* fragments, but *Stachyodes*, *Thamnopora* and rare brachiopod fragments also occur. A few coarse, sand-size grains (less than 10 per cent) are occasionally found between the framework fragments.

There are at least three common modes or origin that could produce a rock of this nature:

(i) It may be an in situ accumulation of branching stromatoporoids essentially in growth position. This could result from the selective growth of only these organisms in any particular environment.

(ii) It may be a lag deposit in which the coarse Amphipora fragments have undergone little transportation while the fines have been winnowed out by wave or current action.

(iii) It could be a bar or beach deposit formed along island shores by dynamic agents, such as currents, waves and wind. This latter interpretation is favoured here.

(3) Vuggy Stromatoporoid Calcirudite (Plate XVI, Figure 6). This rock type is very similar in appearance to the Amphipora calcirudite just described except that Amphipora is not the dominant framework constituent. Stachyodes, massive stromatoporoids, and large gastropod shells are very abundant while lithoclasts, Amphipora, and coral fragments are common; grains and micrite are rare. Minor amounts of calcite, dolomite, and anhydrite spar exist as infill and cement. Porosity is very good.

The same environments postulated for the previous two rock types could also have produced the vuggy stromatoporoid calcirudite. Because of the fragmentary nature of the framework constituents and the abundance of large lithoclasts, however, an accumulation of organisms in growth position is not very probable. Transportation in shallow, agitated water and deposition as a beach or stand line deposit is the explanation which most closely fits the environment of similar deposits found in modern-day reef complexes.

Laminated - Bored Microfacies (f)

These rocks are closely associated and interbedded with those of microfacies (d) and (e) previously described. All three microfacies are believed to represent very shallow water to subaerial environments associated with low-lying islands and bars in the back-reef area. The rock types grouped here within the laminated-bored microfacies are characterized by their paucity of faunas, their light color, and their markedly bored or laminated character. These deposits are interpreted to represent deposition in the intertidal to supratidal environment.

Three rock types are differentiated within this microfacies:

(1) Cream to Light Grey, Bored, Micritic Limestone (Plate XVI, Figure 7). Very light colors, dense micritic nature, "birds-eye" texture, and paucity of skeletal remains are the features that characterize this sediment type. Framework constituents are rare, usually less than 15 per cent, and include gastropods, *Amphipora*, bulbous stromatoporoids, oncolites, and lithoclasts as sparsely scattered fragments. Grains are difficult to distinguish from micrite but are believed to make up 20-40 per cent of the whole rock. Pellets, intraclasts, coated grains, calcispheres and ostracodes are common. Micrite is abundant, 30-50 per cent, and spar is common as infill in borings and vugs. Borings are numerous and this rock often takes on a slightly mottled or laminated appearance. Stringers and blebs of green shaly material are found occasionally in this unit.

This rock type is inferred to have been deposited in a restricted, quiet-water, lagoon-like environment. Increased salinity and long periods of subaerial exposure

are indicated by the paucity of fauna, the numerous well preserved borings, and the dessication features.

(2) Laminated, Sparry Intrapelmicrite (Plate XVI, Figure 8). These sediments are characterized by thin, irregular, discontinuous laminae separated by thin layers of sparry calcite or structureless micrite. Fossils are rare, and often structures such as cracks, broken and curved laminae, and vugs can be seen which may be due in part to dessication. These rocks are very similar to the "laminites" described by Klovan (1963, p. 50). *Amphipora* stems and occasional lithoclasts are the dominant framework constituents which on the whole are rare. Grains are common, consisting of pellets, intraclasts, and coated grains, often agglutinated together. Calcispheres, forams, non-calcareous algae, and ostracodes are plentiful. Micrite is the most abundant groundmass constituent and much is believed to be of algal origin or at least algal trapped. Spar is common as infill and cement between grains and laminae. Spar filled borings are also common.

The laminated rocks are considered to be products of deposition in extremely shallow water, and were often exposed subaerially. By analogy with similar looking present-day deposits, these rocks are inferred to represent algal mat sediments deposited on tidal flats, either on the upper portions of the intertidal zone or in the supratidal zone.

(3) Bored, Laminated Pelsparite (Plate XVI, Figure 9). This rock type is similar to the laminated, sparry intrapelmicrite just described except it has more borings, more sparry calcite, better preserved pellets, and less distinct lamination. Framework constituents are usually not very plentiful though thin, intraformational

conglomerates or beds of coarse debris are common. Abraded coral and stromatoporoid fragments, lithoclasts, and gastropod shells are common in these coarse zones. In the finer-grained zones well preserved pellets are characteristic, though intraclasts, coated grains, psuedo-oölites, and minor skeletal grains are common. The grains are of very fine-to fine-sand size, well sorted, and relatively "clean". A relict laminated structure is evident in these sediments and spar is abundant, especially as infill in the borings, which are characteristic.

This unit has all the features of modern day "beach rock" as described by Ginsburg (1957), Maxwell (1964), and others. It is believed that this rock type represents deposits that formed on low-lying islands and bars in the intertidal zone just seaward of the beach proper, and which became at least semi-lithified before burial.

Reef-Flat, Detrital Microfacies (g)

A mixture of back-reef and organic-reef faunal elements, a light color, and a relatively coarse texture characterizes the sediments of this unit. They tend to be very similar to, and hard to distinguish from, the reef detritus found on the upper fore-reef slopes. The presence of numerous Amphipora, a scarcity of tabular stromatorporoids, and occurrence at a location considered to be a back-reef position, indicates back-reef detritus. Massive stromatoporoids, Amphipora, Stachyodes, and oncolites are common framework constituents, while tabular stromatoporoids, corals, solenoporoid algae, and gastropods are often present in lesser amounts. Skeletal fragments are the most plentiful grains, and micrite (often fine- to medium-silt size) predominates over sparry calcite.

These rocks are taken to indicate shallow, well agitated waters, though not as turbulent as in the reef facies. The reef-flat situated immediately behind the growing organic-reef is the principal environment envisaged for these rock types. It is realized, however, that they could form as detritus on or just in front of the reef as well.

Four rock types are included under this heading:

(1) Stromatoporoid Biomicrite (Plate XVII, Figure 1). Abundant fragmented stromatoporoids, light color, good porosity, and a micritic groundmass characterizes this rock type. The framework (10-40 per cent) contains abundant *Stachyodes* and *Amphipora* fragments, while massive stromatoporoids and to a lesser extent tabular stromatoporoids, corals, algae, and gastropods are common. The framework particles often have a micritic coating (algal?). The grains, which are poorly sorted and subangular, consist largely of skeletal fragments with rare pellets. Both framework constituents and grains are badly altered and recrystallized. The groundmass is predominantly micrite while spar, both calcite and dolomite, occurs as intraskeletal infill. This rock type usually has very good intergranular and intraskeletal porosity.

Reef detritus accumulating in moderately turbulent, shallow water is the interpreted environment. The dead reef-flat located immediately behind the growing organic-reef would be a likely depositional site.

(2) Massive Stromatoporoid Biomicrite (Plate XVII, Figure 2). This rock type is very similar to the stromatoporoid biomicrite just discussed except that rounded massive and bulbous stromatoporoids constitute the majority of the framework. *Amphi-*

pora, Stachyodes, and oncolite fragments occur, while gastropods and brachiopod shells are rare. The framework usually makes up 20-40 per cent of the whole rock. Skeletal grains are abundant while intraclasts and pellets are important locally. Coarse micrite (silty), that has a sugary, porous appearance under the microscope, constitutes most of the groundmass while spar occurs mainly as infill. Pyrite, stylolites, and fractures are rare.

A shallow, moderately turbulent environment is also suggested for this rock type. It may represent deposition close to the organic-reef in the more sheltered areas. Back-reef, reef, and fore-reef positions are all possible for this rock type.

(3) Oncolite Biopelsparite (Plate XVII, Figure 3). An abundance of rounded, algal-coated stromatoporoid fragments (oncolites) distinguishes this rock type. Besides oncolites, massive stromatoporoid, Amphipora, Stachyodes, and brachiopod fragments make up the framework. Sand-size grains are abundant (30-60 per cent) and consist largely of pellets and skeletal grains, though intraclasts, coated grains, and calcispheres are common. The grains tend to be round to subrounded, moderately well sorted, and closely packed. Spar is the predominant cementing agent, though locally micrite is more important. Porosity is patchy and is best in the areas with a high micrite:spar ratio. The coarse micrite appears to have been more susceptible to leaching than the spar.

Deposition on the back-reef flat in shallow, turbulent water is postulated for this sediment. This is indicated by the highly fragmented fossils, oncolites, and abundance of spar.

(4) <u>Skeletal Calcarenite</u> (Plate XVII, Figure 4). This sediment is distinguished by its abundance of sand-size grains and its scarcity of framework constituents. Though discussed here under the back-reef detrital microfacies, skeletal calcarenites are also found in the reef and fore-reef facies. They are also very abundant in the uppermost beds of the reef complex that form the bioclastic unit covering most of the structure. Framework fragments (0-20 per cent) include angular, pebble-size skeletal fragments and a few larger stromatoporoid and coral fragments. The abundant grains (50-70 per cent), almost entirely skeletal in origin, are subangular to subrounded and are only moderately sorted. Both micrite and spar are present as groundmass, the micrite being slightly more plentiful. Porosity is usually good and dolomite spar is common. Stylolites and fractures are rare.

This rock type occurs in a number of environments and is taken to suggest shallow, but only moderately turbulent conditions. It may represent deposition in the more sheltered areas of the reef and reef detritus facies.

(C) Reef Facies:

This facies has been broken down into one microfacies and two rock types. Only rocks that are believed to represent the growing organic-reef in place, and coarse reefoid detritus containing greater than 60 per cent reef framework organisms, many of which are <u>in situ</u>, are placed in this category. The actual wave-resistant, organically constructed framework makes up only a small portion of the rocks. This is understandable since the reef makes up only a small portion of the whole reef complex, and during growth it was subjected to severe biologic and physical destructive agencies.

Massive stromatoporoids characterize this facies and are believed to have been the main reef-building organism. Encrusting stromatoporoids, algae, and corals are common as well. Stachyodes, tabulate corals, tabular stromatoporoids, brachiopods, pelecypods, crinoids, and other more fragile forms thrived within the protection of the massive stromatoporoidal framework. Pockets and lenses composed of a hash of fine skeletal debris are commonly found within the organic framework.

The rocks of this facies are interpreted to have developed in the zone of turbulence along the rims of the complex where reef organisms could flourish in the clear, shallow, well-aerated marine waters.

Massive Stromatoporoid Microfacies (h)

Since only one microfacies is distinguished there is no need to repeat the description given above for the reef facies. The descriptions of the two dominant rock types are as follows:

(1) Stromatoporoid Biolithite (Plate XVII, Figure 5). This rock is composed of massive stromatoporoids and other framework-building organisms that are essentially in growth position. At least 60 per cent of this rock type is compsed of in situ skeletal material preserved as an organic framework. Massive stromatoporoids are the dominant framebuilders but tabular stromatoporoids, encrusting corals and stromatoporoids, and calcareous algae were also important; Stachyodes, brachiopods, crinoids, cup corals, solenoporoid algae, and other organisms grew in the more sheltered parts and are found as individuals or lenses of fossils within the organic framework. Grains are largely skeletal in origin and also occur in small patches intercalated within the

organic framework. The groundmass consists of spar infill and cement with traces of micrite; porosity is usually excellent.

This rock type is interpreted to represent the wave-resistant, organic-reef in growth position and indicates well agitated, moderately-shallow water.

(2) Stromatoporoid Reefoid Limestone (Plate XVII, Figure 6). This unit is made up largely of reef building organisms (40-80 per cent), the majority of which are not in growth position but appear to have undergone only minor transportation. The framework consists of massive stromatoporoid, tabular stromatoporoid, *Stachyodes*, coral, crinoid, algal, and brachiopod fragments. Many of these forms appear to be *in situ*. The large size, angularity, and thinness of many of these fragments indicate that they have undergone little transportation. Many of the stromatoporoid coenostea are heavily bored, fractured, and recrystallized. Grains are abundant and are characteristically skeletal, poorly sorted, and angular. Groundmass is not abundant, with spar and coarse micrite being present in about equal amounts. Much of the micrite appears to be finely ground or altered skeletal material. Porosity is very good.

This rock type is closely associated with the biolithites, and is believed to have formed adjacent to the growing reefs, or represents growing reef that has been broken up and eroded to a certain extent. Shallow, clear, agitated water is envisaged for this environment.

(D) Fore-Reef Facies:

Rocks of this facies consist of detrital components displaced from the reef facies,

indigenous benthonic forms, and pelagic organisms from the open marine environment. The rocks of the upper portions of the fore-reef slope are characterized by an abundance of fragmented reef-dwellers such as massive stromatoporoids, corals, calcareous algae etc.; by a very coarse-grained texture; and are light-colored. Rocks formed at intermediate depths are finer grained, contain less reef-rubble and often show evidence of prolific *in situ* organic growth. The rocks representative of the deep, outer fore-reef slopes are micritic, argillaceous, dark-colored, and characterized by brachiopods, and tabular stromatoporoids. There appears to be a very definite zoning both of fossils and rock types, parallel to the rim of the complex, as one progresses down the fore-reef slope. This is to be expected since the gradual increase in water depth down the fore-reef slope must have exercised considerable control over the type of sediment and organisms that could develop. In general, the rocks of the fore-reef facies indicate deposition in water that was deeper and less agitated than that of the reef facies.

Reef-Flank, Detrital Microfacies (i)

Sediments grouped together under this microfacies are believed to have been deposited on the upper portions of the fore-reef slopes in moderately shallow, turbulent water. The presence of reef-derived rubble with abundant *Stachyodes*, corals, and tabular stromatoporoids distinguish this unit; grains are usually more abundant than micrite. Some of these rock types are very similar to, and may occur as, rocks of the back-reef detrital microfacies.

Five rock types are distinguished under this heading:

(1) *Massive Stromatoporoid Biomicrite* (Plate XVII, Figure 2). This rock type

has already been described in the reef-flat detrital microfacies. It suffices here to say that this rock type is commonly found close to the reef facies on both the seaward and leeward sides.

(2) Coral - Stromatoporoid Biomicrite (Plate XVIII, Figure 1). Numerous branching and massive tabulate corals, solitary cup corals, and branching stromatoporoids dominate this lithology. They are the common framework fossils while tabular stromatoporoid, brachiopod, and crinoid fragments may be present with rare massive stromatoporoids. Grains are predominantly skeletal and are usually coarse, angular, and poorly sorted. Coral, stromatoporoid, brachiopod, and crinoid grains are most common. Both grains and framework constituents are usually altered and recrystallized. The groundmass is not plentiful and is composed of about equal amounts of coarse micrite and spar. Good intergranular and intraskeletal porosity is commonly present.

This rock type is closely associated with the massive stromatoporoid biomicrite, but may represent deposition in slightly deeper water. From the evidence available it appears that the corals thrived in deeper water than did the massive stromatoporoids.

(3) Stachyodes Biomicrite (Plate XVIII, Figure 2). The framework of this unit is composed almost entirely of broken *Stachyodes* coenostea which are the characteristic feature. Crinoid stems, *Thamnopora*, solenoporoid algae, *Amphipora*, and tabular stromatoporoids may be present but are not common. The matrix is similar to the other biomicrites described in this unit, consisting of abundant, relatively coarse skeletal grains, and silt-sized micrite. Porosity is good and this rock type is commonly oil stained.

Deposition in moderately quiet water on the fore-reef slope some distance from the growing organic-reef, is inferred from the lack of reef rubble. The abundance of only Stachyodes fragments indicates a particular environment that allowed the selective growth of primarily one type of organism.

(4) Stachyodes - Tabular Stromatoporoid Biopelmicrite (Plate XVIII, Figure 3). This rock type is highly fragmental and is characterized by an abundance of Stachyodes and tabular stromatoporoid skeletons in a well sorted and rounded matrix. Massive stromatoporoids, corals, solenoporoid algae, and rounded lithoclasts are the other common framework constituents. Grains tend to be more plentiful than framework components and are usually well sorted and rounded. Pellets and skeletal grains predominate and are present in about equal amounts. Some of the pellets have relict internal structure and many may represent well-rounded intraclasts. Dolomite, chert, and quartz occur as authigenic minerals in this rock type but are not plentiful. Dolomite commonly occurs as infill in void space or as replacement of micrite, while the chert and quartz usually occur as a replacement of the larger grains and framework constituents. Stylolites are common and the rock has good intergranular and vuggy porosity.

This rock type is interpreted to represent an accumulation of fore-reef organisms and some organic-reef rubble in relatively shallow water. The fragmented nature of the framework fossils and the well sorted and rounded grains suggests some turbulence during deposition.

(5) Brown to Grey, Biopelmicrite (Plate XVIII, Figure 4). A greyish, crystalline appearance in hand specimen, paucity of framework constituents, and a massive to nodular texture are the features that characterize this rock type. The frame-

work fossils though rare, are diagnostic, consisting for the most part of large, flat brachiopod shells, crinoid ossicles, and gastropod shells. Grains tend to be moderately sorted and rounded and vary both in quantity and type from place to place. Generally, pellets and skeletal grains are most common, with intraclasts and coated grains important locally. Similarly, the type of groundmass varies but micrite is overall the more abundant. This unit often takes on a nodular structure which is especially evident in rocks found on the extreme western flanks of the complex. The rock has undergone considerable recrystallization and replacement; dolomite, pyrite, chert, and quartz are present as authigenic minerals. Stylolites, argillaceous partings, and fractures are common.

These sediments are interpreted to represent wash-off silts and sands, and are low-energy deposits. They accumulated in relatively deep and quiet water on the upper fore-reef slope. This rock type is especially common on the slopes of the extreme western edge of the complex.

Brachiopod - Tabular Stromatoporoid Microfacies (j)

Sediments grouped within this unit tend to be micritic, dark colored, and contain many fossils in growth position, of which tabular stromatoporoids, Stachyodes, brachiopods, and solenoporoid algae are the most common. Argillaceous material, pyrite, and organic matter are common accessories. Micrite is normally much more abundant than grains.

These sediments are taken to represent deposition in relatively deep, quiet water on the lower portions of the fore-reef slope. Three rock types are recognized:

(1) Tabular Stromatoporoid - Algal Reefoid Limestone (Plate XVIII, Figure 5). This rock type is composed largely of tabular stromatoporoids and solenoporoid algae commonly preserved in growth position. Besides these abundant organisms, *Stachyodes*, brachiopods, gastropods, and crinoids are common framework constituents. Grains, though not abundant, occur as scattered fragments "floating" in the micritic or algal-mud groundmass. The grains are predominantly skeletal and are poorly sorted and angular. Micrite is abundant (30-40 per cent), and is light colored and often mottled. Much of the silty micrite is believed to be finely-ground algal particles while solenoporoid algae can often be found that grade into, or are altered to, a massive micritic rock with no visible algal structures. This grain-diminution (see Wolf, 1965) of solenoporoid algae to micrite is believed to have been very important here and possibly in many other sediments as well. It may have been especially important in the back-reef limestones that contain a high proportion of micrite.

This rock type is believed to represent *in situ* organic growth and reefoid detritus formed by algal-strom. patch reefs growing on the fore-reef slope. Solenoporoid algae and tabular stromatoporoids were the principal organisms present and they appear to have thrived in moderately deep, quiet waters subjected to gentle currents but no turbulent wave action.

(2) Stachyodes - Tabular Stromatoporoid, Micritic Limestone (Plate XVIII, Figure 6). This lithological unit is very similar to, and is associated with, the algal-stromatoporoid reefoid limestone just described. The principal difference being that this sediment has a greater abundance of *Stachyodes* and less evidence of solenoporoid algae. Tabular stromatoporoids though present are far less abundant. Micrite is very

abundant and is similar in color and appearance to that found in the algal-stromatoporoid limestone, but evidence of an algal grain-diminution origin for it is not evident. Most is believed to represent finely abraded rather than altered or recrystallized algal or skeletal material. This rock is generally dense having a few vugs partially or completely filled with spar.

A similar environment of deposition as for the tabular stromatoporoid, algal reefoid limestone is postulated for this rock type. It is, however, believed to represent more clastic than in situ biogenetic deposition, and as such, may have formed behind or between the growing patch reefs on the fore-reef slope.

(3) Dark Brown, Brachiopod - Stromatoporoid Biomicrite (Plate XVIII, Figure 7). A dark brown color, a fine-grained texture with abundant micrite, and abundant brachiopods distinguish this rock type. The framework (20-40 per cent) is made up primarily of brachiopods, tabular stromatoporoids, and Stachyodes; though cup corals, gastropods, crinoids, solenoporoid algae, bulbous stromatoporoids, and bryozoans occur. Many of the brachiopods and tabular stromatoporoids appear to have intact skeletons. Grains are more abundant here than in the other rock types of this microfacies and are largely skeletal, angular, and poorly sorted. Groundmass is common (20-50 per cent), and consists of micrite, argillaceous material, and carbonaceous matter. Pyrite, dolomite, chert, and quartz are accessory minerals. Stylolites are abundant.

These deposits are believed to represent deposition on the outermost and deepest portions of the fore-reef slope. The water was probably relatively deep, quiet, and murky due to suspended micrite and argillaceous matter.

(E) Off-Reef Facies:

The dark, argillaceous limestones and calcareous shales of the Waterways Formation are grouped within the off-reef facies. This includes the so-called basin rocks that occur laterally to the east and above the complex as well as the channel deposits that separate the Carson Creek North reef complex from similar buildups to the north, west, and south.

Dark brown, micritic, argillaceous limestone dominates the lithology while interbeds of dark brownish grey shale are common. Laminated, nodular, brecciated, or massive structures characterize these sediments. Brachiopods, crinoids, gastropods, ostracodes, calcispheres, and Tentaculites are the common minor constituents.

The nature of these rock types indicates deposition in quiet, possibly stagnant water though local shallower areas with some water agitation prevailed close to the edge of the reef complex.

Three rock types are recognized:

(1) Reef-Rubble Limestone (Plate XVIII, Figure 8). This diagnostic rock type was also recognized and described by Jenik (1965). It is characterized by its location just above, or at the top of, the reef complex; its high pyrite and microfossil content; and by its brecciated or nodular appearance. It is usually less than one foot thick and is commonly found only in the back-reef wells. Rounded lithoclasts or nodules of micritic limestone form the bulk of the framework, but small brachiopod, gastropod, crinoid, and echinoid fragments are common. Sand-size grains are not common and consist of skeletal fragments and whole ostracode, foraminifera, calcisphere, and

Tentaculites skeletons. Micrite and argillaceous matter are common with some spar infilling vugs, fossil cavities, and fractures. Pyrite is a common accessory mineral.

This rock type signifies the death of the reef complex and Jenik (1965) interprets it as representing an increase in the depth of the water. This zone is taken here to indicate, however, a shallowing of the water covering the back-reef portions. This would correspond with the erosional top of the reef complex found in the rim wells. It is postulated that while large portions of the reef complex were above water, this reef-rubble zone formed in shallow, restricted marine pools at times subjected to erosion and brecciation.

(2) Argillaceous, Nodular Limestone (Plate XVIII, Figure 9). Grouped together here are the argillaceous limestones having a definite brecciated appearance with distinct, angular lithoclasts; and, the more nodular limestones in which the lithoclasts are rounded or elongated due to compaction. These rocks are commonly found as channel or basin deposits laid down close to the reef complex. The lithoclasts or nodules, which are the predominant framework constituents, consist of dark yellowish brown, micritic limestone enclosing numerous skeletal and non-skeletal grains. A few brachiopods and branching stromatoporoid, crinoid, and coral fragments constitute the rest of the framework. Surrounding the framework constituents, the matrix consists largely of dark brown, argillaceous limestone that has a laminated or bedded appearance due to argillaceous or stylolitic layers. Skeletal grains are common in the matrix and are poorly sorted. Pyrite, chert, quartz, dolomite, and clay minerals are present.

This type of sediment is believed to have formed in moderately deep, slightly agitated water in the off-reef or basinal environment. The numerous lithoclasts are

believed to be from two sources. Some represent material transported from the reef to the quieter off-reef areas by storms, etc., while the majority probably represent "boudinage" type lithoclasts formed by the compaction and disruption of thin limey beds.

(3) Shaly, Micritic Limestone (Plate XVIII, Figure 10). Dense, dark brownish grey, argillaceous, micritic limestone interbedded with thin, brownish black, fissile shale layers characterize this rock type. Framework constituents and grains are rare to absent. Commonly the groundmass, consisting largely of shale or micritic limestone, makes up 80 to 90 per cent of the whole rock. Pyrite is the only common accessory mineral recognized. Brachiopods, usually the inarticulate types, are the only fossils commonly found in these sediments.

Because of the shale content, dark color, thin bedding, micritic character, and scarcity of fossils, this rock type is interpreted to have been deposited in relatively deep, quiet, stagnant waters.

CHAPTER 7 - GEOCHEMISTRY

Introduction

Though numerous studies on the geochemistry of carbonate rocks have been published, few have dealt specifically with individual reef complexes to see if there are any geochemical criteria that can be used as facies indicators. When an exploration well has penetrated a reef complex, it is a problem of great economic importance in the oil industry to be able to tell in which physiographic zone or facies the well is situated (Ingerson, 1962). This is especially critical in Swan Hills type reefs, where the best porosities are in the outer rim facies, and geophysical methods are not dependable for outlining the shape and extent of the reef buildup. If the facies can be recognized, land acquisition, drilling, and development programs following up wildcat strikes will be far more successful. It is the purpose of this phase of the present study to search for geochemical criteria that can be used in conjunction with petrographical and paleontological data to differentiate the various reef facies and microfacies. It is also hoped that the geochemical data will help in the interpretation of environment conditions and be of value for correlative purposes.

Here, elemental analyses were made for the most part on whole rock samples, while only a few determinations were carried out on the acid-soluble fraction. According to Keith and Degens (1959) total rock analyses are less significant than analyses of separated fractions for environmental studies. Hirst and Nicholls (1958) suggest that to best illustrate the sedimentary character of an element in a given environment the amount of the element in both the detrital and non-detrital fractions should be calculated.

Chester (1965) points out that the trace elements in the non-detrital portion (acid-soluble) should best reflect the character of the chemical environment of deposition, while the detrital fraction reflects the character of the source material and the physical variables of the depositional area. In the present study, for example, curves representing the Sr and Mg content in the various facies are similar for both the total rock and acid-soluble samples. Likewise, Chester found for the Sturgeon Lake reef that the curves comparing the Ni, Cr, V, and Co content in the reef and off-reef facies were of a similar nature for both the total rock and non-detrital analyses. It is thus proposed that for geochemical studies on reef complexes similar to the Carson Creek North, wherein facies and environmental indicators are the principal goals, analyses of whole rock samples are often as useful as those of the so-called non-detrital fractions. The reason for this belief is that the chemical composition of the water over the reef complex probably did not vary greatly except for certain restricted and extremely saline areas in the back-reef lagoons. The physical variables of the water, however, such as its depth, turbulence, and muddiness, etc., had a great influence on the types of organisms and sediment present in any one environment. Thus, total rock analyses, which are more of a reflection of the physical variables in the various environments, are believed to be just as important in this case for strictly environmental and facies indicators as analyses of the non-detrital fractions, and they are easier to obtain. The methods used, the operating conditions of the instruments, and the calibration curves are briefly outlined in Appendix II. The evaluation of the analyses, giving the errors, precision, and standard deviations are discussed in Appendix III.

X-Ray Fluorescence Analyses (Total Rock Samples)

General:

More than one hundred and fifty samples from four wells were analysed for eight elements. The elements chosen; Sr, S, Ca, Mg, Mn, Fe, Al, and Si are readily determined by x-ray fluorescence methods and are present in large enough amounts to be detectable. The quantitative analytical determinations were made on a Phillips Norelco fluorescence unit using standard x-ray spectrochemical techniques. Operating conditions and calibration curves for the various elements are listed in Appendix II.

The amounts of the elements present in the various microfacies of the four cores analysed are illustrated by the histograms in Figures 15 to 18. These diagrams show the core footage represented by the samples, and also portray the amount of variation of the elements between the different facies. The average element content of each facies and microfacies is listed in Table 6 and diagramatically illustrated in Figure 19. The element variations between the different facies and microfacies indicates the possibility of their use as environment indicators. Figure 19 also reveals the close relationship between the amount of an element present in a sample and the inferred water depth in which it was deposited.

In addition to the Carson Creek North studies, twenty-five samples from the Redwater reef complex were analysed for the same elements, except S. The samples were selected from core slabs that appeared to represent the different facies recognized by Klovan (1964). Figure 20 diagrammatically shows the average values for the various Redwater facies as well as those found for the Carson Creek North samples.

Table 6. - Average Values of Total Rock Analyses

Facies	Micro-facies	N	Sr ppm.	S Wt.%	CaO Wt.%	MgO Wt.%	MnO Wt.%	Fe_2O_3 Wt.%	Al_2O_3 Wt.%	SiO_2 Wt.%
Reef Platform	a	29	273	.62	53.68	.87	.0079	.22	.34	1.39
Back-Reef	b	23	209	.14	54.93	.69	.0058	.11	.21	.37
	c	8	148	.16	55.37	.50	.0059	.15	.14	.24
	d	4	107	1.67	12.16	2.28	.0124	4.64	20.71	24.66
	e	8	167	.17	55.05	.53	.0054	.11	.16	.34
	f	18	191	.13	55.02	.67	.0059	.11	.17	.31
	g	24	199	.14	55.19	.62	.0059	.10	.11	.25
Reef	h	13	195	.11	55.22	.67	.0053	.09	.08	.23
Fore-Reef	i	9	232	.11	55.04	.68	.0063	.11	.12	.32
	j	17	280	.18	54.29	.99	.0082	.19	.19	.70
Off-Reef	k	4	255	1.02	32.36	1.73	.0195	2.31	9.14	17.51
Back-Reef* Average		81	183	.15	55.11	.60	.0058	.12	.16	.30
Fore-Reef Average		26	256	.15	54.66	.84	.0072	.15	.15	.51

N = number of samples used in analyses.

* excluding values for green shale microfacies (d).

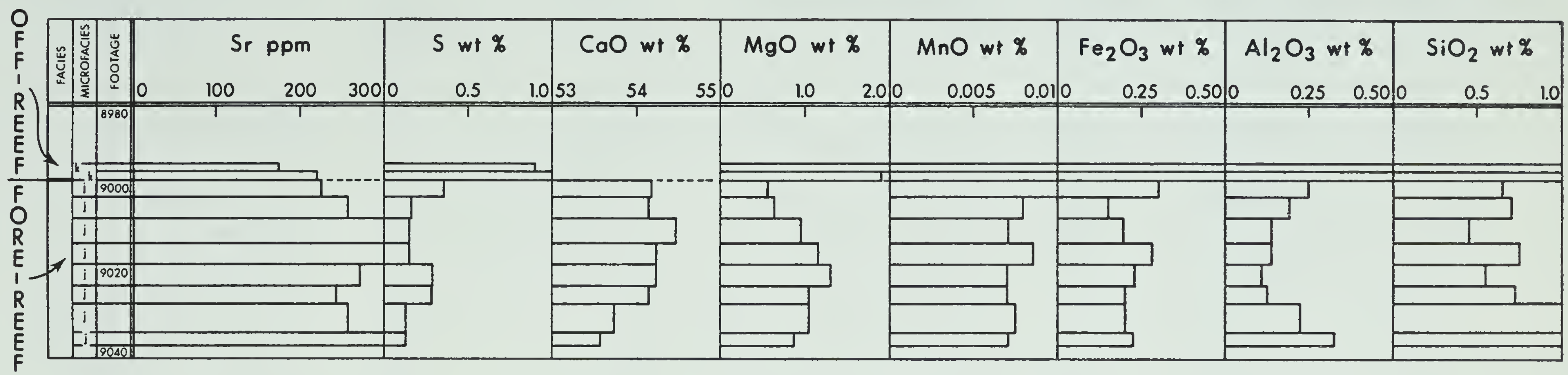


Figure 15. X-ray Fluorescence Analysis of Core Samples from Well 6-7-62-12W5
(Carson Creek North Reef Complex)

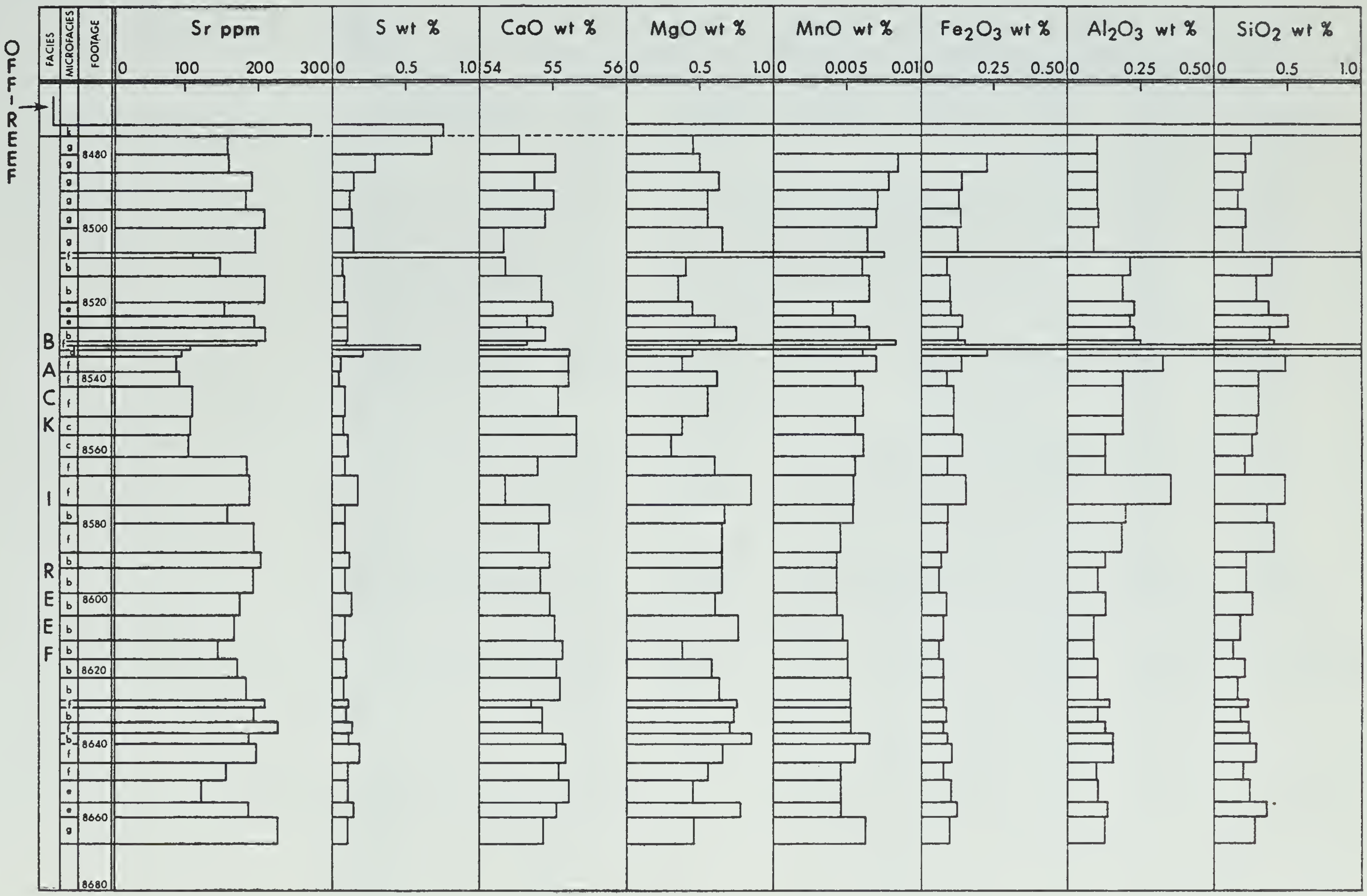


Figure 16. X-ray Fluorescence Analysis of Core Samples from Well 6-4-62-12W5
(Carson Creek North Reef Complex)

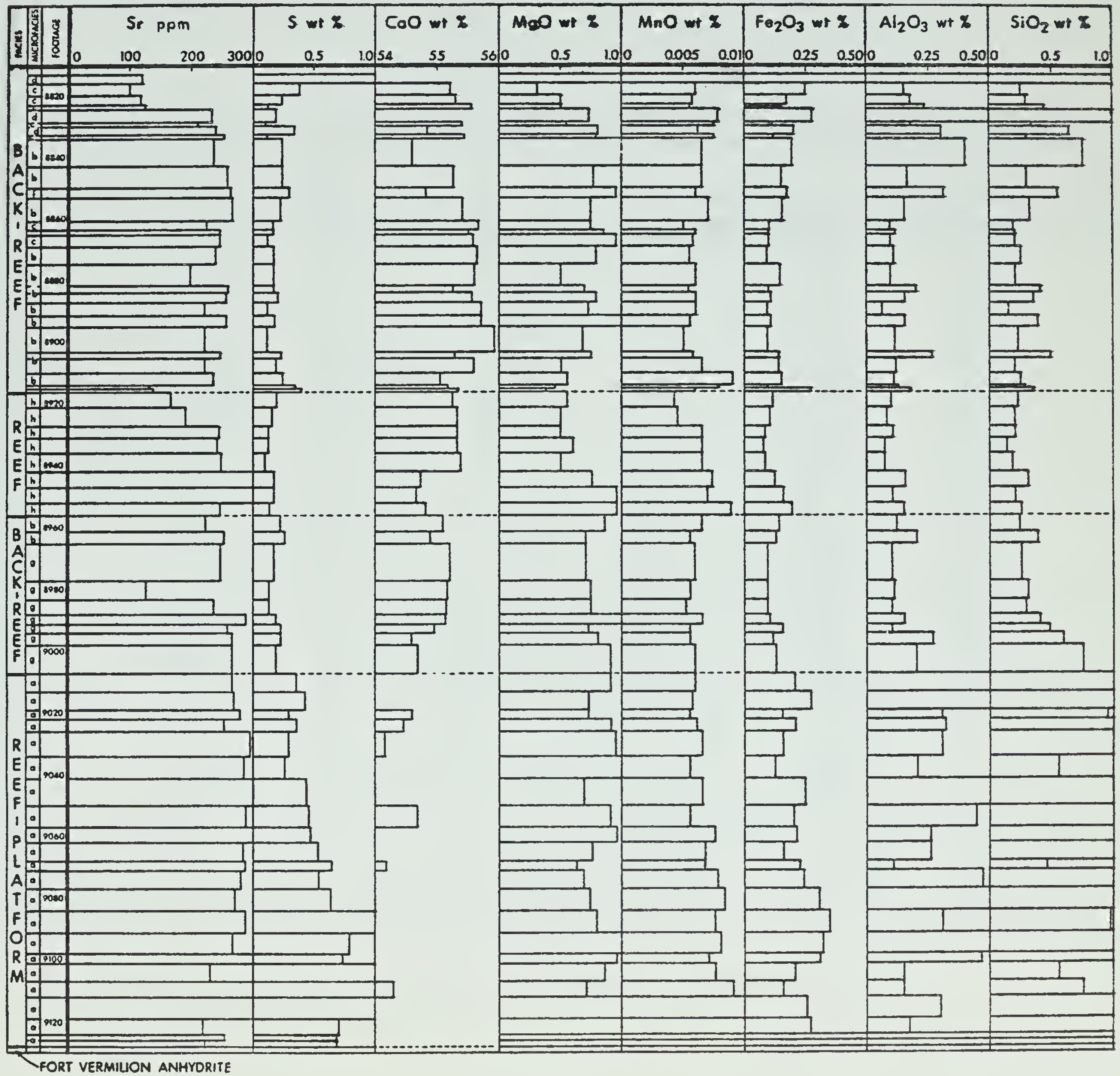


Figure 17. X-ray Fluorescence Analysis of Core Samples from Well 6-1-62-12W5 (Carson Creek North Reef Complex)

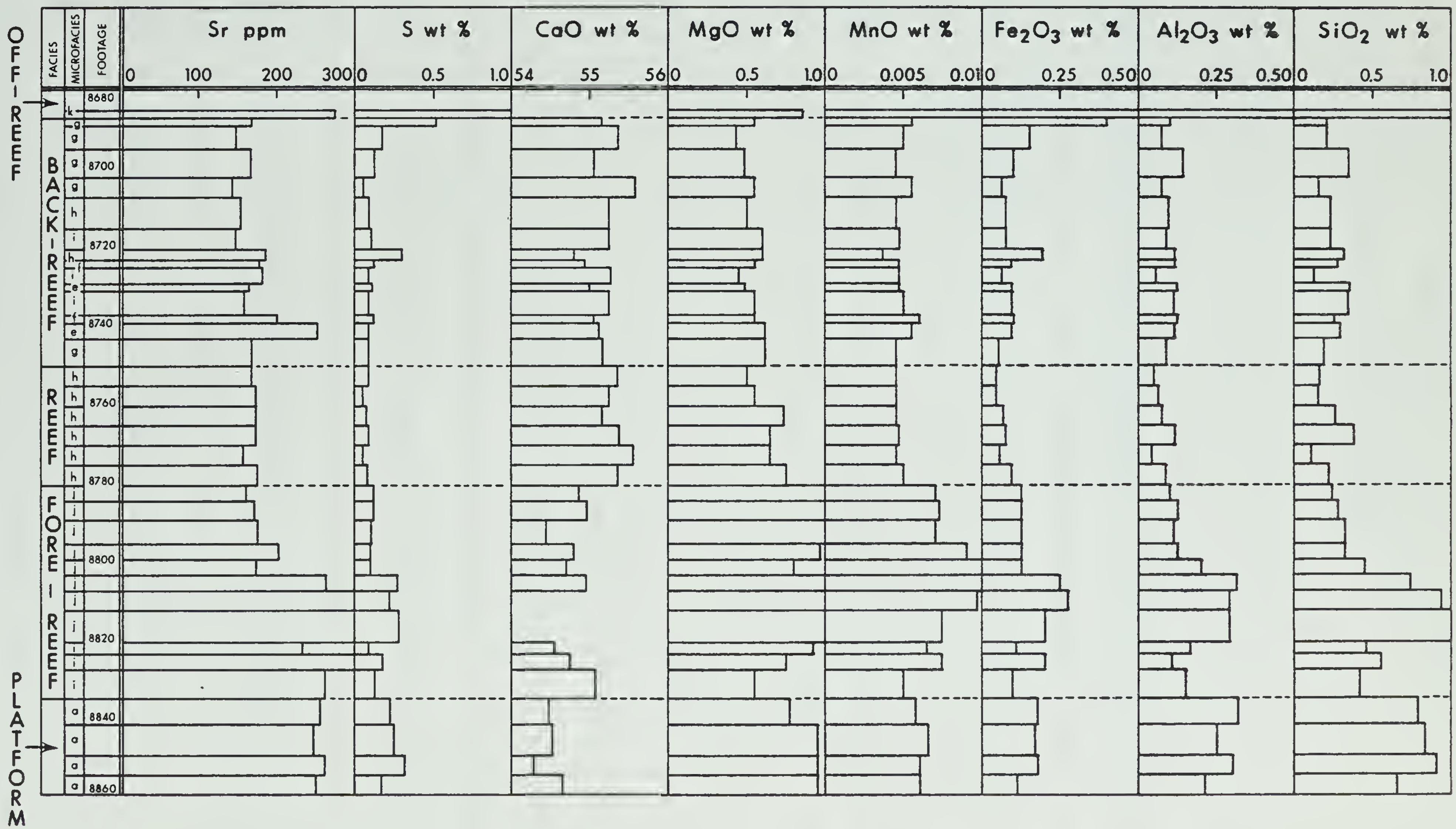


Figure 18. X-ray Fluorescence Analysis of Core Samples from Well 16-6-62-11W5
(Carson Creek North Reef Complex)

A very brief account of the distribution and environmental significance, of the various elements is presented in the following pages.

Results:

Figure 19 shows that the distribution curves for the elements Mg, Mn, Fe, Al, and Si are very similar and can therefore be discussed together. These elements are concentrated in the off-reef facies and to a lesser extent in the reef platform facies, rather than in the reef complex facies. This is to be expected since they are concentrated in the clay and detrital minerals which petrographic data shows are most common in the deeper, more quiet-water, off-reef and reef platform limestones. Within the reef complex itself there are far less diagnostic variations found between the back-reef, reef, and fore-reef facies for these five elements. In general, the reef limestones and the shallow-water, pure, back-reef limestones have the lowest values for these elements, while the fore-reef and some of the darker back-reef rock types have the highest values. Perhaps the most interesting feature of Figure 19 is the similarity in the shape of the "curves" of these five elements to the profile of the reef complex. This postulated reef profile showing the relative water depths was derived from petrographic and paleontologic data, and its similarity to the compositional curves has very important implications. It suggests that an approximation to reef-complex profiles may actually be constructed from bulk chemical composition data when it is presented in a manner similar to that shown in Figure 19. If this premise can be shown to hold true for most reef complexes regardless of age or location, then it provides us with an important tool for future reef studies and oil exploration. Though only two reef complexes were studied, the similarity in their results as shown in Figure 20, and

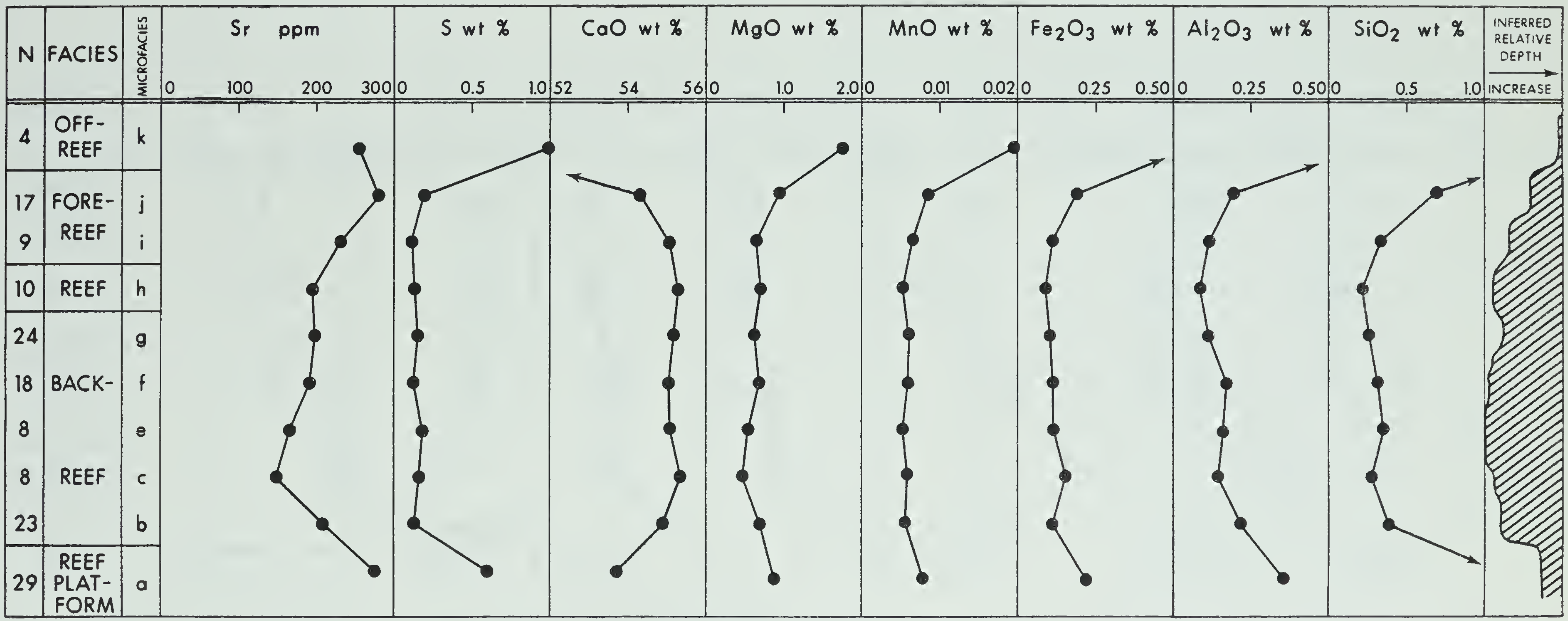


Figure 19. Averaged Whole Rock Analyses for the Various Facies and Microfacies of the Carson Creek North Reef Complex.
(green shale microfacies (d) omitted).
N = number of samples used in analyses

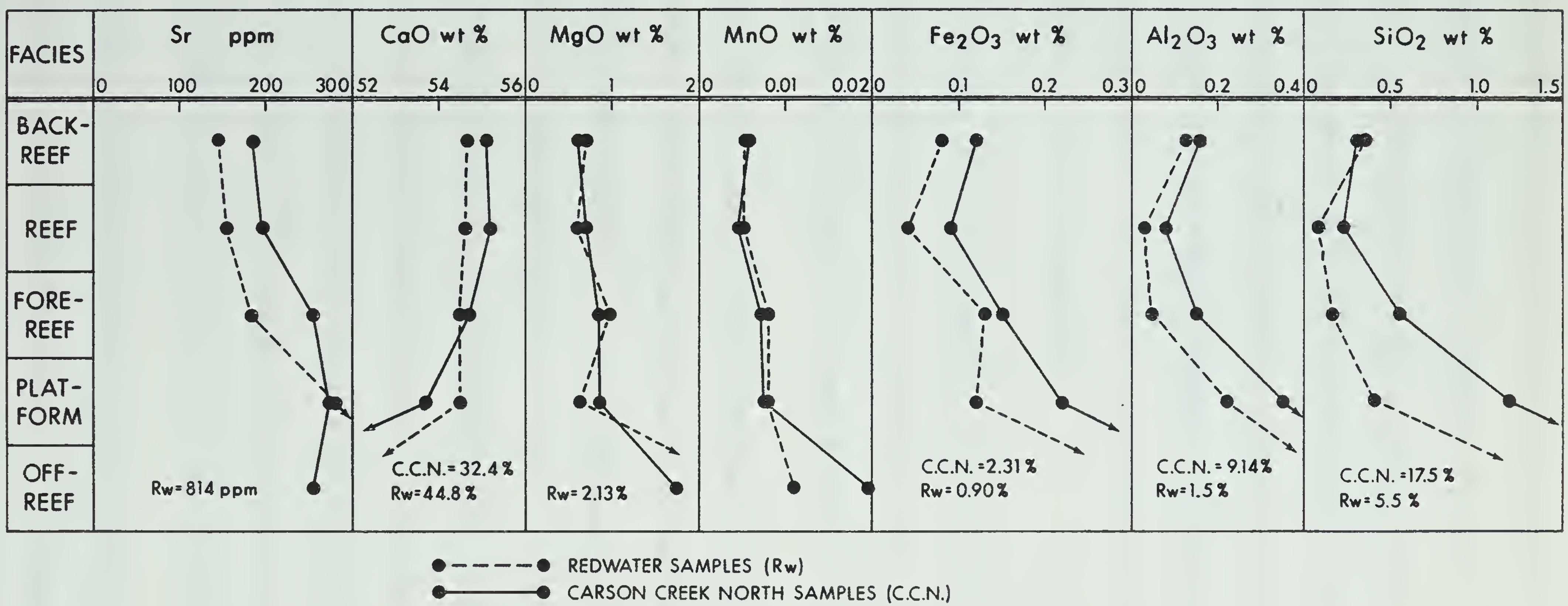


Figure 20. Comparison of X-ray Fluorescence Analyses for the Carson Creek North and Redwater Reef Complexes

the fact that all reef profiles are related to bulk chemical composition (since the topography in part controls the sedimentation) suggests to the writer that reef profiles can be obtained for most reef complexes by a comprehensive geochemical study. From Figure 21 it can be seen that the curve for the insoluble residue variation closely follows that for the above five elements and also reflects the topographic profile of the reef complex. This again stresses the fact that the variations in the total rock analyses are governed by the amount of detritus; which is in turn governed by the reef topography and the physical variables at the site of deposition.

Most of the Al and Mn found in the samples is present in the form of clay minerals. The Fe is present largely as pyrite and clay minerals, while the Mg is concentrated as the mineral dolomite and is present to a lesser extent in the clay minerals.

The curve for S variation as shown in Figure 19 does not differ greatly from the characteristic pattern except that it shows less variation in the reef complex facies than do the previously discussed elements. This may be because the S is largely in the form of pyrite which is principally diagenetic in origin in the reef complex facies and is not necessarily directly governed by sedimentation factors. The predominance of S in the off-reef and reef platform limestones is due to the presence of considerable argillaceous and organic matter and the quiet, reducing nature of the depositional environment. Thus the variation in S also is largely due to the depth and energy conditions at the site of deposition (which conditions also govern the detrital content).

The Sr and Ca curves are the only two that vary to any degree from the characteristic pattern of the Mg, Mn, Fe, Al, Si, and S curves. This is largely because these two elements are controlled by the carbonate or non-detrital phase to a much greater

extent than are the other elements.

The distribution of CaO as shown in Figure 19 illustrates the inverse relationship of this curve to the others. This is to be expected since the CaO increases with decreasing detrital mineral content while the other elements increase with increasing detrital content. Practically all of the calcium present is in the form of the mineral calcite. Minor amounts are present as dolomite, while traces may be supplied by sulphates and other minerals.

The Sr distribution curve illustrates its preference for the off-reef and reef platform facies, but also shows that it has distinct variations in the reef complex facies. The increase in Sr in going from back-reef, to reef, to fore-reef, to basin, found here for the Carson Creek North and Redwater reef complexes, and by Sternberg, et al. (1959) for the Triassic Steinplatte reef complex in Austria, indicates that Sr has promise of being a very important environmental indicator in reef studies. The distribution of Sr in sediments is probably governed by a large number of factors, but in the Carson Creek North limestones the depth of the water, the amount of skeletal material, and the proportion of clay minerals present appear to have been the most important. In general, the greater the water depth during deposition and the more unaltered skeletal or argillaceous material present in a sample, the greater will be its Sr content.

Figure 20 compares the averaged element values of the five major facies for both the Carson Creek North and the Redwater samples. The close agreement of the curves representing the element variations for the two different reef complexes is very gratifying and encouraging. This agreement between the two sets of data indicates that geochemical variations may be very useful in helping to differentiate the

inter-related facies and physiographic zones found in ancient reef complexes.

Spectrophotometer Analyses (Acid-Soluble Fraction)

General:

Forty-one samples were selectively dissolved in acetic acid to determine the amount of Sr, Mg, and Ni in the acid-soluble (carbonate) portion. The elements Sr and Mg were also determined in the whole rock samples, while the trace element Ni was determined only in the acid-soluble portion. The amount of insoluble residue in the samples left after the acid treatment was also determined. Acetic acid was used to dissolve the limestones so that the clay materials would not be broken down or leached (see Hirst and Nicholls, 1958, p. 474). For a discussion of the methods and graphs used in the spectrophotometer analyses the reader is referred to Appendix II.

The average values of the elements in the various reef-complex microfacies are tabulated in Table 7 and illustrated in Figure 21. The distribution of the three elements and the insoluble residue between the various facies is illustrated in Figure 22(a). Figure 22(b) compares the average values of all the samples taken from a fore-reef well (16-6-62-11W5) to those taken from a well with a back-reef location (6-4-62-12W5).

Results:

Figure 21 shows the close relationship between insoluble residue content and a

Table 7. - Average Values of Acid-Soluble Analyses

Facies	Microfacies	N	Insoluble-Residue Wt.%	Sr ppm.	Mg ppm.	Ni ppm.
Reef Platform	a	4	2.55	206	4270	1.92
	b	2	.7	141	2740	1.69
	c	2	.4	77	1250	1.42
Back-	d	2	65.3	112	4529	21.02
Reef	e	3	.8	150	2752	.85
	f	5	.6	120	2408	1.00
	g	3	.6	137	2297	.42
Reef	h	8	1.1	143	3126	.65
Fore-	i	6	.9	118	2216	.59
Reef	j	3	1.6	138	5853	1.03
Off-Reef	k	2	27.5	235	5737	3.68
Back-Reef Average*		15	.6	125	2289	1.08
Fore-Reef Average		9	1.3	128	4035	.81
Average Values in Back-Reef well(6-4-62-12W5)		9	.6	111	2210	1.47
Average Values in Fore-Reef well (16-6-62-11W5)		24	1.0	138	3088	.64

N = number of samples used in analyses.
* excluding values for green shale microfacies (d).

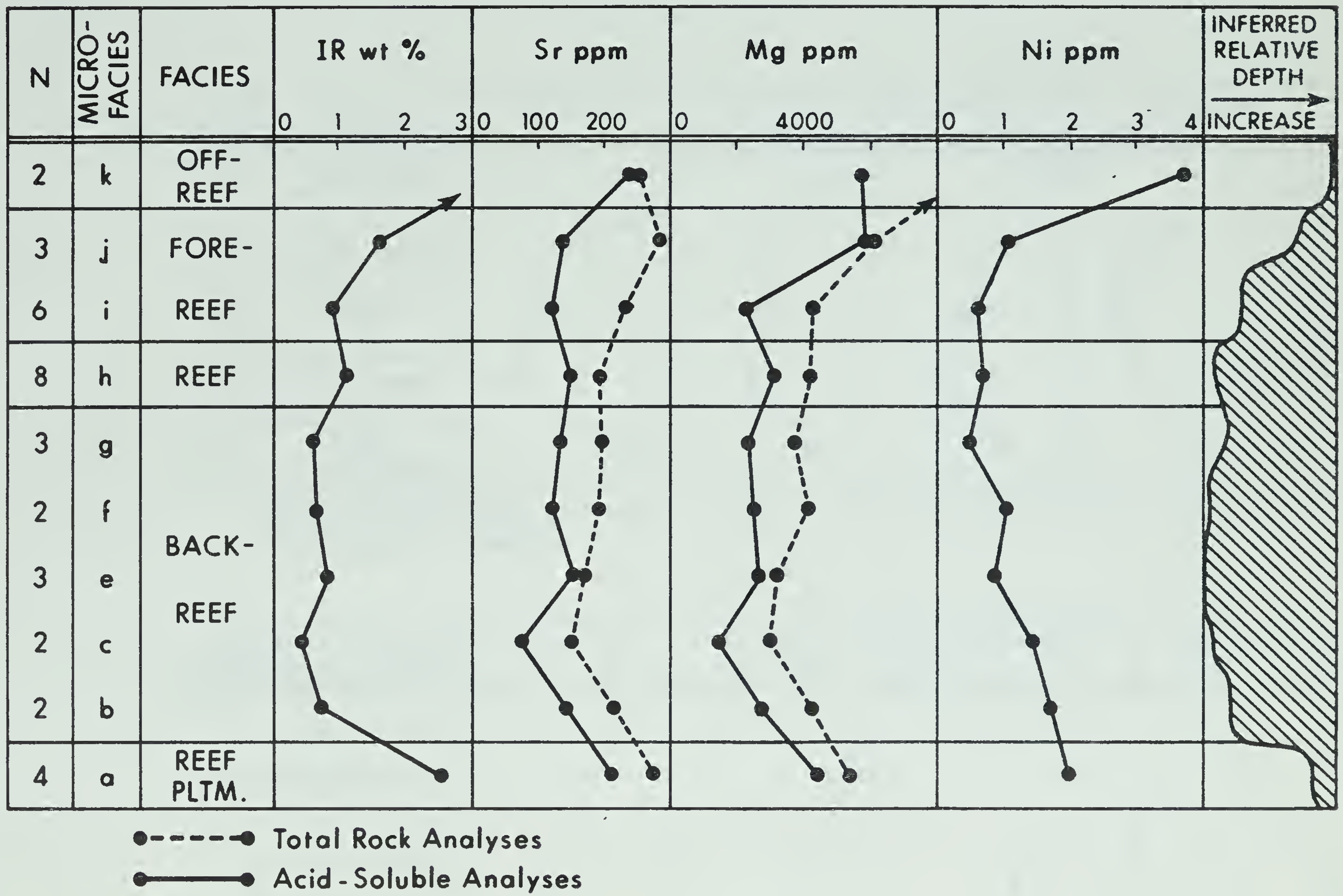


Figure 21. Averaged Acid–Soluble Analyses for the Various Facies and Microfacies (green shale microfacies omitted), of the Carson Creek North Reef Complex

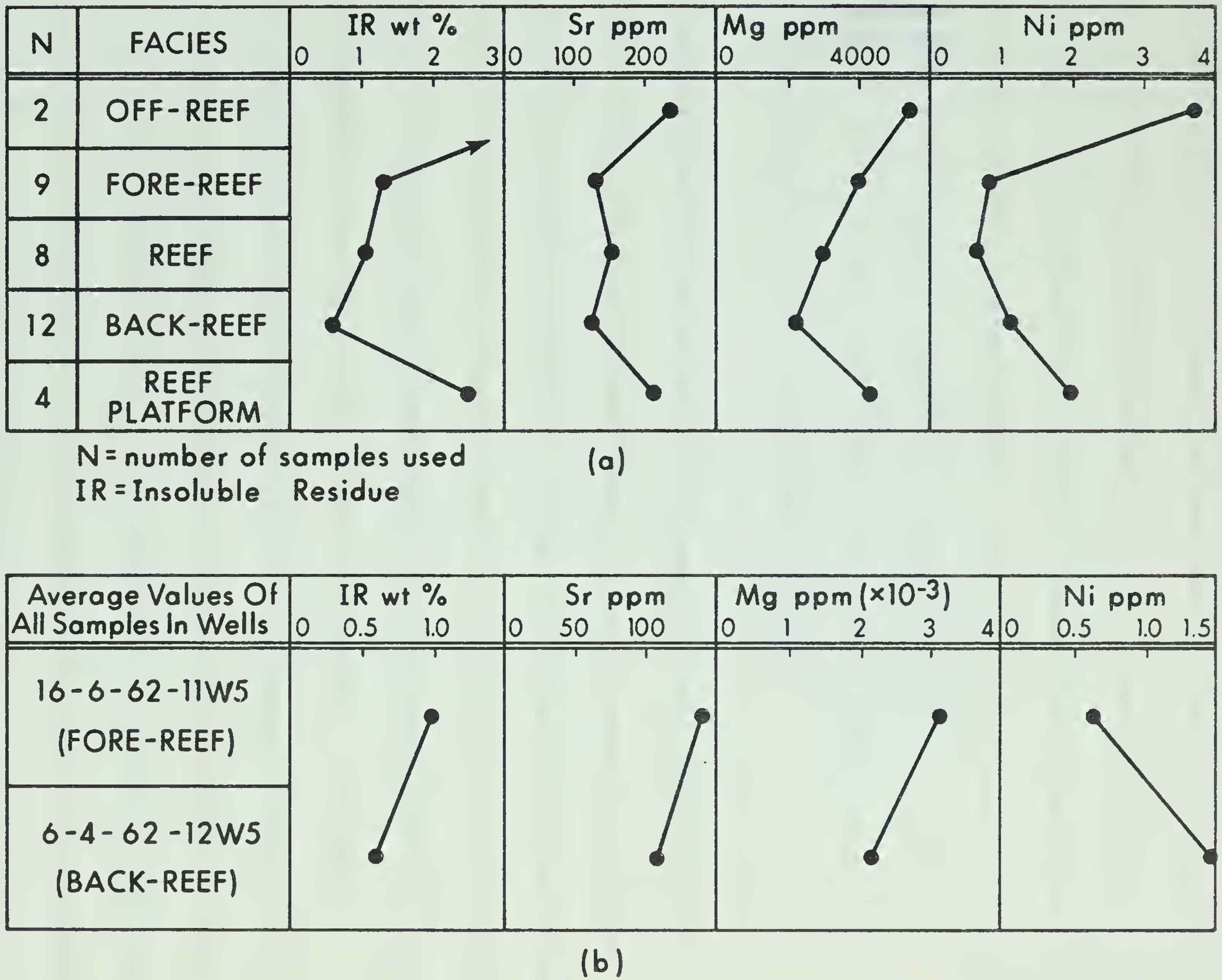


Figure 22. Averaged Acid-Soluble Analyses of the Carson Creek North Reef Complex Facies

postulated relative water depth in which the rocks were deposited. Also, comparison with Figure 19 shows the similarity of the insoluble residue curve to the Mg, Mn, Fe, Al, and Si curves and illustrates the fact that total compositional variations are only a reflection of the amount and type of detritus, which is in turn governed by the topographic profile and the physical variables of the depositional area. Argillaceous matter, organic matter, pyrite, quartz, chert, and iron oxide make up most of the insoluble residue found in the Carson Creek North limestones.

The distribution of Sr for the acid-soluble samples is very similar to that for the total rock samples. The acid-soluble values are somewhat lower, and indicate that the clays have a greater concentration of Sr per unit volume than do the carbonates. Since the Sr in the acid-soluble portions is present as a substitute for Ca in the carbonate minerals, the variations found in these samples should be more significant for environmental interpretations than are analyses of whole rock samples. The similarity between the two sets of data for Sr as shown in Figure 21, however, does not substantiate this conclusion and suggests that the same factors have controlled the Sr content in both cases. Thus, increase in depth of water and amount of skeletal and argillaceous matter appear to be complimentary interacting factors and the main ones governing the Sr content in both the acid-soluble and total rock portions of the reef complex limestones. How much recrystallization and diagenetic processes have influenced the effects of these original factors cannot be readily determined.

The distribution for Mg in the acid-soluble fraction is very similar to its distribution in the total rock samples as shown in Figure 21. For the reef complex facies, the similar amounts of Mg found in the acid-soluble and total rock samples, indicates

[illegible]

[illegible]

[illegible]

that the majority is supplied by the mineral dolomite. For the off-reef, reef platform, and green shale facies, however, the difference in amount between the two sets of analyses is more widespread suggesting that the presence of magnesium bearing clays are an important source for the Mg.

The nickle distribution curve is somewhat different from that of the other elements studied in that the Ni is more concentrated in the back-reef rather than the fore-reef facies. It is interesting to note that the average Ni concentration for the acid-soluble fraction of the reef complex limestones (about 1.5 ppm) is much lower than that given by Chester (1965) for the Sturgeon Lake reef facies (Average 22 ppm). Re-runs of the Carson Creek North samples agree within the pre-determined confidence limits suggesting that either the two reef complexes are very different in Ni content or that the values of Chester (1965) are too high. In two of the Carson Creek samples the insoluble residues were analysed and showed an average content of about 100 ppm Ni. This indicates that the detrital portion of the Carson Creek North limestones contain much more Ni than the acid-soluble carbonate portion. Tests were also carried out on Ni spiked samples to see if any of the Ni in the carbonate portion was being absorbed by the detrital fraction during the acid-solution process. These tests showed that no discernable amounts of Ni were lost from the acid-soluble portion during the dissolution of the samples.

Figure 22(a) clearly shows that the average values for Sr, Mg, Ni, and insoluble residue content are distinctly higher for the off-reef and reef-platform facies than for the reef complex facies. Within the reef complex, the average Sr values for the back-reef and fore-reef samples are very similar and appear to be of little use in

differentiating these facies. The Mg and insoluble residue, however, are definitely concentrated in the fore-reef limestones whereas the Ni shows a distinct preference for the back-reef rock types.

Figure 22(b) emphasizes the concentration of the insoluble content, Mg, and Sr in the fore-reef, and Ni in the back-reef positions. Figure 22(b) also indicates that Mg and Ni should make a good pair for the construction of a facies indicator ratio.

Summary and Conclusions

Data obtained from the present study suggests that there is real geochemical differentiation among the various reef complex and off-reef facies. It is believed that these variations can be very useful for determining and characterizing the various environments of reef sedimentation. The total rock, and to a lesser extent the acid-soluble, compositional variations are believed to be due principally to the amount and type of detritus present. The detrital content in turn is a direct reflection of the reef topography and physical variables of the depositional environment such as water depth and energy, etc.

In the limestones studied, the off-reef samples show the highest concentrations of all elements except Ca. The reef platform limestones tend to have element contents that are intermediate between those for the off-reef and reef complex facies. Within the main reef complex facies, the fore-reef samples have the highest Sr, Mg, Mn, Fe, Si, and insoluble residue content; intermediate S and Al values; and the lowest Ca and Ni determinations. The reef samples were highest in Sr (acid-soluble samples) and Ca; intermediate in Sr (whole rock samples), Mg,and insoluble residue;

and lowest in S, Mn, Fe, Si, and Ni. The back-reef samples were highest in Ni, Al, and Si (Redwater samples); intermediate in S, Ca, Mn, Fe, Si (Carson Creek North Samples); and lowest in insoluble residue, Sr, and Mg.

The chemical composition of the green shale microfacies (d) is so different to that of any of the other microfacies (see Tables 6 and 7) that it was not included in any of the diagrams. The chemistry of this shale indicates that its mode of formation was very different to that of the off-reef shales, and strengthens the conclusion reached earlier from the petrographic data that this rock type is a residual deposit formed by subaerial solution and erosion.

An interesting and promising result derived from this study is the way in which the reef profile tends to be outlined by the bulk composition or the element variation curves. This illustrates the fact that reef topography plays a very important part in controlling the nature of sedimentation from a chemical point of view as well as lithologically and paleontologically. Future studies with more control points may show that position in a reef complex can be obtained from topographic profiles that are based on the trends of chemical variations and detrital contaminant values. If so, this would be of tremendous value to the oil industry.

Another feature of direct interest to the oil industry is the use of a geochemical study such as the present one in well studies in which no core but only drill chips are available. In these cases it is often extremely difficult to tell from a petrographic study of the chips in which facies or physiographic zone of a reef complex a well is situated. The rock chips, however, would permit a complete geochemical study that could indicate the well's position in the complex.

The variations among facies as presented in this study are believed to be real for most of the elements studied, since they are greater than the pre-determined confidence limits or precision values of two standard deviations. How much these variations can be attributed to depositional influences in contrast to post-depositional factors, however, cannot always be determined.

It is realized that the geochemical variations and criteria found in this study may not apply to all ancient reef complexes. The close similarity between the Redwater and Carson Creek North results are, however, encouraging and suggest that at least the western Canada Devonian reef complexes are chemically very similar. Also, since the major element distributions, as determined by whole rock analyses, are simply a reflection of the amount and type of detritus present, the author suggests that the geochemical distribution pattern will not markedly differ from one reef complex to another unless the nature of the reef-building process varies. No quantitative limits have been assigned to the elements characterizing the various facies since the writer feels a more regional study involving a number of reef complexes is necessary before values can be used in an absolute rather than in a relative context as in the present study.

CHAPTER 8 - DIAGENESIS

Introduction

Diagenesis as used here includes those changes that occur in a sediment or sedimentary rock after the initial stage of deposition and preceding the onset of metamorphism. The pressure-temperature conditions that prevail during diagenesis are not widely removed from those existing close to the earth's surface.

In the Carson Creek North limestones evidence of several different types of diagenetic change can readily be found, but in general, post-depositional alteration has not occurred to the extent that the original character and previous history of the sediment cannot be determined. For this reason the complexities of the broad subject of diagenesis are only briefly touched upon in this report. The following are some of the principal diagenetic processes and effects found in the rocks of the Carson Creek North reef complex.

Biological Diagenesis

Studies of recent carbonate sediments have shown that organisms play a profound role in the early stages of diagenesis. Such processes as eating, burrowing, excretion, and moving by various types of macroscopic organisms tend to change the character of sediments in a number of ways such as: reduction of particle size, mixing of sediment, extraction of organic matter, and changes in chemical composition, color, etc. Also, the activity of bacteria and other microscopic organisms change the physico-chemical character of bottom sediments to probably an even greater extent than the more

obvious macroorganic activity. Though not so readily recognizable, biotic activity was probably just as important in the diagenesis of ancient limestones as it is in recent carbonates.

In the Carson Creek North limestones features interpreted as organic burrows are the most commonly found form of biological diagenetic activity. In the deeper-water, off-reef and fore-reef limestones, examples of sediment-filled burrows are fairly common (Plate XIX, Figure 1) and certain areas of disrupted primary stratification have been attributed to burrowing organisms. In the back-reef limestones evidence of burrowing activity is abundant, especially in the laminated-bored microfacies. Here, burrows are commonly filled with sparry calcite (Plate XIX, Figure 2) rather than with the surrounding sediment. This is taken to indicate that the host material was at least partially consolidated at the time of boring. Only a few borings in the hard parts and shells of organisms have been recognized (Plate XIX, Figure 3), but this phenomenon was probably an important process in the disintegration and alteration of skeletal material. In particular, algal corrosion of limestone fragments, especially skeletal remains, is believed to have been very important. Evidence of this process can be seen throughout the limestones in the form of algal-coated grains in various states of preservation (Plate XIX, Figure 4). Mottling, especially that found in the dense non-skeletal microfacies, is believed to be due in part to organic mixing after deposition.

Direct evidence of biological abrasion and size reduction of carbonate particles has not been found, largely because it is probably impossible to differentiate this material from that broken by physical agencies such as waves, etc. It is prob-

PLATE XIX

Biological Diagenesis, Compaction, Cementation, and Lithification

Figure 1. Borings. Hand specimen showing mixing of sediment by burrowers and examples of sediment filled borings, X0.7 (Location, 6-32-61-11, 8654').

Figure 2. Borings. Peel (negative photograph) showing spar filled borings, X1 (Location, 16-5-62-11, 8614').

Figure 3. Borings. Peel (negative photograph) showing a burrow and borings filled with internal sediment and sparry cement, X0.8 (Location, 6-36-61- 12, 8590').

Figure 4. Algal corrosion. Amphipora fragment coated and altered by non-calcareous algae, X8 (Location, 16-6-62-11, 8842').

Figure 5. Internal sediment and spar infill. Vug, possibly an organic boring, filled with three distinct layers of internal sediment and two layers of calcite cement, X9 (Location, 6-36-61-12, 8480').

Figure 6. Stylolite. Hand specimen of a stylolite showing considerable relief, X0.7 (Location, 16-5-62-11, 8614').

Figure 7. Compaction nodules. Hand specimen of a nodular or "boudinage" argillaceous limestone, X0.7 (Location, 16-26-61-12, 8671').

Figure 8. Compacted pellets. Micritic limestone that on close examination is seen to consist largely of compacted and merged pellets, X22 (Location, 16-6-62--11, 8837').

Figure 9. Fringing and equant calcite cement. Thin section of a vug filled with a thin layer of fringing calcite cement enclosing coarsely crystalline equant calcite cement, X22 (Location 6-11-62-12, 8813').

Figure 10. Overgrowth calcite cement. Thin section showing crinoid fragments surrounded by overgrowth calcite cement in optical continuity, X28 (Location, 16-31-61-11, 8544').

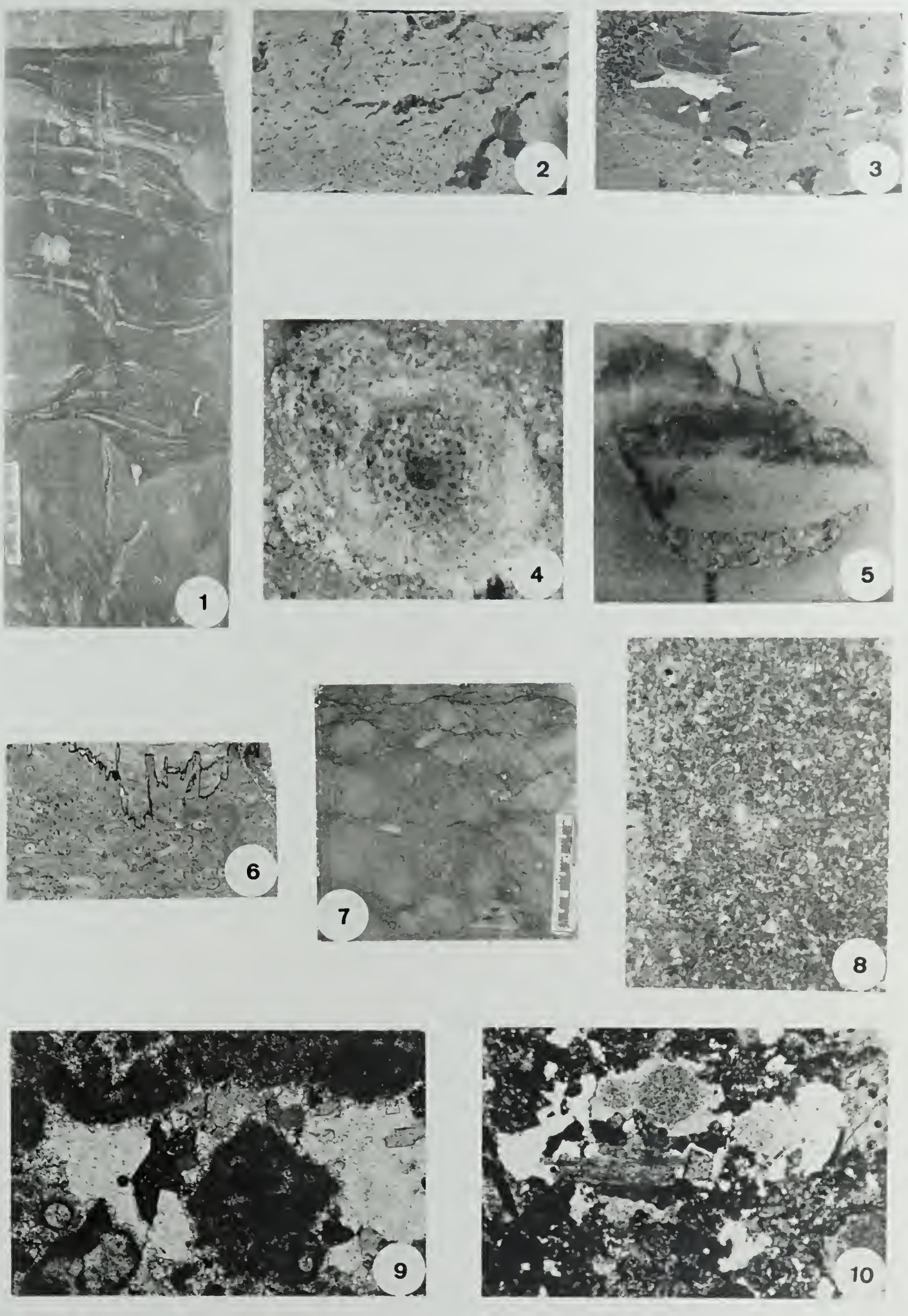


PLATE XIX.

able, however, that biologic activities were responsible for much of the broken and abraded fossil fragments that are so common in the reef facies and reef detritus.

Though the exact role played by organisms in the formation of ancient rocks can never be completely deciphered, analogies with recent carbonates would suggest that biotic activity was in the past, as it is now, one of the most important influences in the early diagenesis of carbonate rocks.

Compaction

Compaction is the reduction in bulk volume of a sediment caused by the individual rock particles being pressed together by the weight of the overlying sediments. The degree of compaction in carbonate sediments depends to a large extent upon the degree of early rigidity or lithification of the sediment, the amount of porosity, the packing and fabric of the particles, and the thickness of overburden which accumulated. The common results of compaction in limestones are reduction in porosity and expulsion of interstitial water, deformation and crushing of fossils, and a thinning of the rock unit.

According to Pray (1960), and Beales (1965), there is a lack of any significant compaction in most carbonate rocks. They make this generalization to include not only the coarsely-textured carbonate rocks but the calcilutites as well. Other workers, such as Newell et al., (1953) and Powers (1962), however, have suggested that the finer-grained limestones, at least, have undergone considerable compaction. In this study the available evidence, with the exception of the numerous stylolites, suggests

that the majority of the reef complex limestones have undergone little compaction. The off-reef argillaceous limestones appear to have undergone more, though still not a great deal of compaction. Most of the compaction in these sediments, especially in the finer-grained types, probably occurred during the first foot of burial when most of the porosity, organic matter, and moisture content was lost (see Ginsburg, 1957, p. 91).

The following features were found to illustrate the lack of compaction in most of the Carson Creek North limestones:

(1) Pellets, intraclasts, and other grains, except in very few cases, are still rounded or do not have a squashed or flattened appearance (Plate II, Figure 6).

(2) Grains usually do not have sutured or micro-stylolitic boundaries (Plate II, Figure 6).

(3) Borings and other voids now commonly filled with sparry calcite show no evidence of early diagenetic distortion or compaction (Plate XIX, Figure 5).

(4) The algal-laminated sediments appear relatively undisturbed from original growth position (Plate XVI, Figure 2).

(5) There is little evidence of post-depositional crushing of shells in most of the limestone.

(6) There is a similarity between the sediment under shells or in other uncompacted cavities to that of the surrounding unprotected areas.

(7) The lack of draping of the off-reef limestones over the reef complex is taken to indicate that only minor compaction has occurred in the off-reef limestone.

(8) Laminations are well preserved in some of the reef complex as well as in the off-reef sediments (Plate XXI, Figure 9).

On the other hand, there are certain features found in the limestones that tend to indicate considerable compaction, such as the following:

(1) The presence of numerous stylolites, especially in the finer-grained, more argillaceous rocks (Plate XIX, Figure 6).

(2) Micritic limestone which on close examination can be seen to consist largely of pellets and intraclasts that have been compressed together to the extent that their boundaries have merged and are no longer clearly distinguishable (Plate XIX, Figure 8).

(3) The presence of so-called nodular or "boudinage" limestones that show evidence of compaction and plastic deformation (Plate XIX, Figure 7).

(4) Laminations, argillaceous layers, and Amphipora stems, etc., that tend to bend over and under larger stromatoporoid fragments and nodules. This feature is most commonly found in the off-reef and reef platform limestones (Plate XIX, Figure 1).

Though the evidence is not clear cut, it appears that the majority of the reef complex limestones underwent only minor compaction. The reef and reef-detritus rocks were only slightly compacted because they were deposited largely as rigid masses of hard skeletal parts. Many of the back-reef limestones were associated with periodic or continuous subaerial exposure and thus became lithified or cemented at an early stage. This early consolidation would tend to inhibit compaction. The remaining deeper-water, back-reef and fore-reef limestones that were probably deposited as softer, more "soupy" sediments underwent more compaction and these rocks are the ones that tend to show the most evidence for compaction, along with the off-reef and reef platform limestones.

Cementation and Lithification

Cementation as used here is the precipitation of minerals around grains and matrix particles or in the interstices of a sediment. It produces rigidity in a sediment and tends to reduce the porosity and permeability. Cementation is believed to be one of the most important lithification processes along with recrystallization and compaction.

In the Carson Creek North limestones calcite is by far the most abundant cement found; dolomite is common; silica, anhydrite, and iron oxide are rare. Four principal modes of occurrence of calcite cement as noted in the rocks under discussion are as follows.

(a) Fringing calcite cement.

(b) Equant calcite cement.

(c) Overgrowth calcite cement.

(d) Fracture-filling calcite cement.

(a) The fringing calcite cement (Plate XIX, Figure 9) consists of bladed or fibrous crystals that line cavities and voids or form "fringes" around larger particles. The elongated crystals tend to be oriented with their long axis perpendicular to the surface of deposition. This is usually the first cement to be deposited in a rock and is believed to be an early diagenetic event. Recent studies have shown it to readily form in sediments that have been subaerially exposed, but it may also originate during early burial by precipitation from entrapped sea water. Though it is somewhat similar in appearance and fabric to the post-lithification dog-tooth spar found lining veins and geodes etc., it has been found in the Carson Creek North limestones lining only original or depositional voids. As pointed out by Powers (1962, p. 141),

modern studies indicate that this thin drusy coating forms shortly after deposition and is the first step towards lithification in many cases. This statement is endorsed by the findings of the present study.

(b) Equant calcite cement (Plate XIX, Figure 9) refers to the precipitated, cavity-filling spar whose crystals are more or less randomly located and equidimensional in shape. This calcite tends to partially or completely fill the centre of cavities not already occupied by the earlier formed fibrous calcite. This category of calcite cement includes both the "granular cement" (cement between detrital particles) and the "drusy mosaic" (cement growing into all other cavities) of Bathurst (1958).

In contrast to the fibrous calcite cement, equant calcite is common both in depositional voids and in secondary or late diagenetic cavities. Its early mode of formation is evidenced by its presence in borings, dessication and slump fractures, etc., that are undeformed and not filled with overlying sediment. Its late diagenetic generation is evidenced by its presence in secondary pores and solution voids that tend to transect many depositional features.

The presence in large amounts of equant calcite in a rock is the principal factor in reducing the primary porosity, and it also tends to be important in the complete lithification of a sediment.

(c) Overgrowth calcite (Plate XIX, Figure 10) refers to the calcite cement that is deposited on grains as an optically oriented overgrowth. This type of cement is rare, being best developed around crinoid fragments, though on occasion it occurs around other fragments as well. This corresponds to the "rim-cement" of Bathurst (1958).

The time of formation of this type of cement is hard to establish but it is believed to have formed later than the fibrous calcite and earlier than much, and in conjunction with some, of the randomly oriented, equant calcite cement.

(d) Fracture filling calcite (Plate XXII, Figure 8) is a common type of cement found in the Carson Creek North limestones. Fractures tend to vary from very early diagenetic (dessication cracks, slump fractures, etc.) to very late post-lithification joints that cut across all the other depositional and diagenetic features. The sparry calcite cement associated with these fractures is therefore considered to represent several periods of deposition ranging from early to very late diagenetic.

The general lack of compaction and the evidence of considerable early cementation suggests that lithification was probably a comparatively early event in many of the reef-complex limestones. The presence of well-preserved, spar-filled borings and algal laminations indicate early lithification, as do sediments that are very similar to, and interpreted as being ancient examples of, recent carbonate beach rock. Also, the presence of numerous intraclasts and larger lithoclasts indicates areas of lithified or at least partially consolidated bottom sediment that was available for erosion and deposition in adjacent areas.

Though many of the early lithified sediments are believed to have been situated above sea level for considerable periods of time, subaerial exposure is probably not necessary for lithification, in carbonate sediments. It may, however, be necessary for early diagenetic lithification. As pointed out by Ginsburg (1957), Friedman (1964), and others, extensive cementation and lithification in recent carbonates has been found only in rocks that are at least partially exposed above sea level. Friedman

concludes, however, that lithification analagous to that under subaerial conditions can probably occur in the subsurface. According to Maxwell (1964), subaerial exposure is not necessary for early lithification since bonding in a sediment can be accomplished by various processes performed by noncalcareous algae.

Neomorphism

Folk (1965) introduced the term neomorphism to embrace the processes of inversion (aragonite to calcite), recrystallization (calcite to calcite), and strain-recrystallization (strained calcite to unstrained calcite), where the gross composition is kept constant. This term does not include the process of cementation (simple pore-space filling) or replacement (change in gross composition). In ancient carbonate studies such as the present one this term is particularly useful since it is almost impossible to tell which of the lithological constituents were originally aragonite and which were calcite. Within the reef-complex limestones, alteration and recrystallization in one form or another have been very important diagenetic processes. Close examination of fossils, especially those in the reef and fore-reef areas, show that almost all forms have been recrystallized to a certain extent. Two of the more interesting and important aspects of neomorphism, however, recognized in the Carson Creek North limestone are the following: algal grain-diminution and the development of coarse sparry calcite.

Algal Grain-Diminution:

Considerable evidence has been found in the Carson Creek North limestones for the alteration of algal masses to micrite. Wolf (1965) calls this type of diagenetic

formation of micrite, "grain-diminution". Though the exact mechanisms involved in algal grain-diminution are not certain, solution and degrading recrystallization (neomorphism) are the two most likely processes responsible for the change. Plate XX, Figures 1 and 2 show the change in algal colonies from clearly recognizable algal material to micrite in which little or no algal features are visible. Grain-diminution of solenoporoid algae was found to be prevalent in some of the micritic fore-reef limestones, especially in the algal - tabular stromatoporoid reefoid limestones. Though less evident, much of the micrite in the back-reef may also be due to grain-diminution of algal colonies. The numerous oncolites and micrite-coated fragments are believed to be the result of algal coatings in which the cells and filaments have been destroyed leaving only laminated micrite layers. As pointed out by Wolf (1965, Figure 3), however, in these cases it is usually hard to tell whether a former cellular or filamentous algal colony changed diagenetically to micrite or whether the micrite is a direct algal precipitate. The abundance of micrite, calcisiltite, and fine sediment in the Carson Creek North limestones that can be shown to have originally been algal in origin suggests that algal grain-diminution by one means or another was a very important process.

Sparry Calcite Formation:

Diagenetic neomorphism of micrite to coarse sparry calcite is a common phenomenon in the Carson Creek North limestones (Plate XX, Figure 3). Though not as prevalent as in the lime muds, partial or complete neomorphism of allochems and larger fossils to spar has also been observed. Much of the coarse micrite or calcisiltite that is so common, especially in the reef and reef detritus, may also be a product of

PLATE XX

Neomorphism and Dolomitization

Figure 1. Algal grain-diminution. Polished section (reflected light) of a *Parachaetetes* fragment that shows alteration to micrite along the upper surface, X10 (Location, 16-6-62-11, 8830').

Figure 2. Algal grain-diminution. Two algal fragments in which parts still have recognizable algal texture (white) while the rest has been altered to micrite (medium grey) X6 (Location, 6-11-62-12, 8830').

Figure 3. Neomorphism. Thin section of an algal nodule that has been partially altered to micrite and then to sparry calcite in the centre, X9 (Location, 16-6-62-11, 8828').

Figure 4. Neomorphism. Thin section showing relict micrite patches floating in neomorphic spar, X22 (Location, 6-11-62-12, 8813').

Figure 5. Neomorphism. Thin section of a pelsparite in which the centers of many pellets have been recrystallized to crystalline spar, X22 (Location, 16-6-62-11, 8828').

Figure 6. Dolomitization. Polished section (reflected light) of dolomite spar (white) replacing the matrix and cutting into the *Stachyodes* fragment in the right half of the photograph, X15 (Location, 6-32-61-11, 8689').

Figure 7. Dolomitization. Stained thin section showing patchy calcite (dark grey) in a dolomite mosaic (white) that shows traces of relict grains (very light grey) X9 (Location, 6-32-61-11, 8689').

Figure 8. Dolomitization. Stained thin section showing porphyroblastic dolomite rhombs in a micrite groundmass, X22 (Location, 6-36-61-12, 8480').

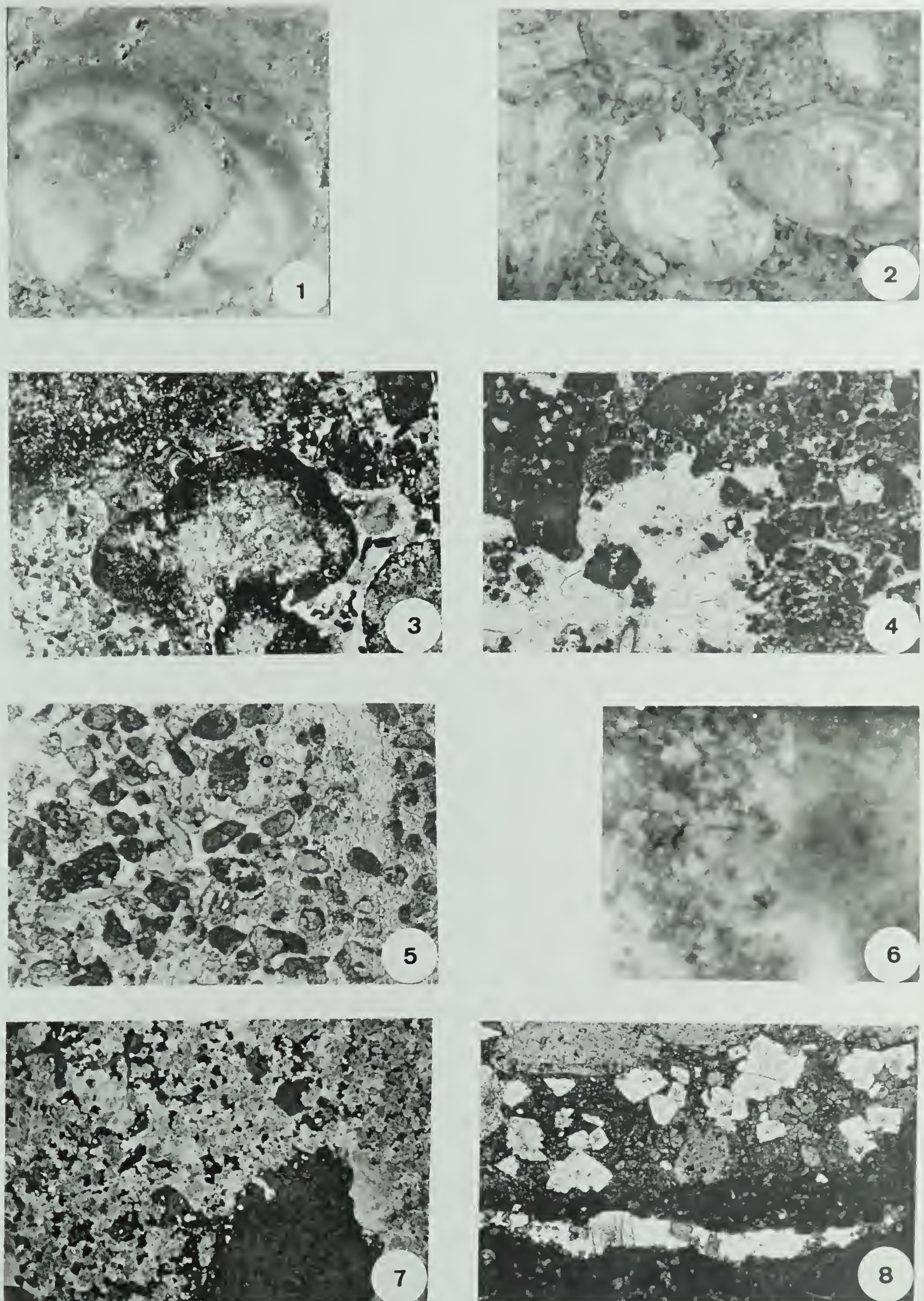


PLATE XX.

neomorphism but the majority is believed to be detrital carbonate silt. Though the formation of neomorphic calcite spar is believed to have been an important diagenetic process, it appears to have been less important volumetrically than calcite spar cement formed through precipitation. The following types of evidence for the formation of neomorphic calcite have been found in the present study:

(a) Grains "floating" in coarse spar (Plate XX, Figure 5).

(b) Transection of allochems by spar, or formation of embayed borders (Plate XX, Figure 6).

(c) Presence of pellets and other allochems that show varying degrees of alteration to spar. Occasionally only the "ghost" borders of the grains are left (Plate XX, Figure 5).

(d) The often "patchy" or mottled appearance of this type of calcite.

(e) Presence of remnant patches or micrite inclusions "floating" or trapped within the sparry calcite (Plate XX, Figure 4).

Though the above criteria for neomorphic calcite spar are valid forms of evidence; in many, or perhaps most cases, such diagnostic features are lacking. As concluded by Folk (1965, p. 45) there is no easy way to distinguish neomorphic sparry calcite from pore-filling spar. For a complete discussion of the criteria used to distinguish the various types of calcite the reader is referred to Bathurst (1958) and Folk (1965).

The relative times at which the various neomorphic changes took place cannot be established with any degree of certainty. Aragonite to calcite inversion, algal grain-diminution, and the formation of fringing calcite cement may have been relatively

early since these phenomena commonly occur in recent carbonates. The time of neomorphic sparry calcite formation, though undetermined, may have been a much later diagenetic effect.

Authigenic Noncarbonate Minerals

Dolomite, silica (chert and quartz), and pyrite are the principal noncarbonate diagenetic minerals found in the Carson Creek North limestones. Though unimportant volumetrically, these minerals have a number of different modes of occurrence and are important for diagenetic and environmental studies.

Dolomite:

Though not abundant, dolomite is an important accessory mineral in certain areas of the reef complex. Petrographic and geochemical data both indicate that dolomite is much more abundant in the fore-reef limestones than in the other reef complex facies. A preference of dolomite for the fore-reef rock types was also noticed by Jenik (1965). As suggested by Jenik (1965, p. 61) the susceptibility of the fore-reef limestones to dolomitization and silica replacement may be due to the ease of migration of magnesium and silica rich solutions in that position. The nearness of the argillaceous basinal sediments as a source for these solutions and the excellent porosity of the fore-reef limestones make this suggestion attractive.

As stated previously, dolomite is rarely present in large enough amounts to destroy the original textures. It is commonly associated with calcite spar, and like it, is believed to have had more than one mode of formation. In general, however,

the available evidence indicates that most, if not all, the dolomite is secondary, having originated during diagenesis. Equant dolomite cement associated with equant calcite cement is perhaps the most common type found. This dolomite commonly fills the voids between grains or intraskeletal pores and it is hard to tell whether it is a replacement product of the sparry calcite or is an authigenic precipitate. Another type of dolomite found consists of scattered crystals or a mosaic that replaces matrix, allochems, and fossil fragments (Plate XX, Figure 7). This dolomite is definitely a replacement mineral as shown by the relict patches and "ghost" outlines of the original fragments in the spar. Dolomite also occurs as scattered, euhedral rhombs in some of the micritic limestones and in the internal sediment of certain voids or shell cavities (Plate XX, Figure 8). This dolomite is believed to represent either primary precipitation or a very early diagenetic event.

Late diagenetic dolomite occurs in fractures that tend to transect the other textural features. Because of the various modes of occurrence, no one general theory can be applied to either the mode or time of formation of the dolomite found in this study.

Silica:

Silicification is not a common feature of the Carson Creek North limestones, but authigenic silica has been found as three distinct variaties: spherulitic chalcedony, chert nodules, and euhedral quartz crystals. Like dolomite, the silica tends to be concentrated in the fore-reef and off-reef limestones.

The spherulitic chert occurs largely as a replacement of calcite, especially brachiopod shells (Plate XXI, Figures 1 and 2), and commonly shows concentric banding or growth rings. The more massive type of chert occurs largely as chert nodules (Plate XXI, Figure 4) or as small isolated patches replacing parts of individual fossils or grains. These chert lenses, which are about 1 1/2 inches in thickness and at least 3 inches wide, tend to be subparallel to the stratification, have irregular borders with the surrounding limestone, contain numerous fossils both silicified and unsilicified, and appear to have formed by replacement of the original carbonate rock. The exact mode of formation and source of the silica is, however, unknown. These lenses were found only in the reef platform, off-reef, and deep fore-reef rock types.

Quartz is present as small, elongated, euhedral crystals that are occasionally associated with chert but more often occur as isolated prisms (Plate XXI, Figures 5 and 6). The quartz, like chert, is a replacement product and appears to have selectively replaced the larger fossils and grains rather than the finer-grained surrounding matrix. Also, within the replaced skeletons the quartz is usually found as a replacement of the actual shell parts rather than occurring within the voids or pores as silica cement or as a replacement of the sparry calcite infill. Why the silica preferentially replaced the shells and skeletal parts rather than the matrix and voids is not known. It has not been determined whether the silica replacement was early diagenetic or late diagenetic, but the available evidence indicates that it was later than much of the calcite spar formation, with the possible exception of that filling late diagenetic fractures.

PLATE XXI

Silica and Pyrite Authigenesis

Figure 1. Silicification. Thin section showing chert replacement of fossils and matrix, X13 (Location, 16-5-62-11, 8603').

Figure 2. Silicification. Stained polished section showing spherulitic chert replacement (white) of a brachiopod shell, X5 (Location 16-5-62-11, 8601').

Figure 3. Silicification. Thin section showing almost complete replacement of carbonate by chert, X22 (Location, 16-5-62-11, 8603').

Figure 4. Silicification. Peel (negative photograph) showing a fractured chert lense (dark grey) in argillaceous limestone (medium grey), X0.8 (Location, 6-7-62-12, 9004').

Figure 5. Silicification. Thin section showing euhedral quartz crystals with relict calcareous centers replacing an altered stromatoporoid? fragment, X9 (Location, 16-26-62-11, 8565').

Figure 6. Silicification. Polished section of euhedral quartz crystals similar to Figure 5, X10 (Location 16-26-62-11, 8565').

Figure 7. Pyritization. Thin section showing pyrite cubes lining a calcite spar filled vug, X9 (Location, 16-5-62-11, 8627').

Figure 8. Pyritization. Hand specimen of reef rubble zone showing replacement of fossils by pyrite, X0.8 (Location, 6-7-62-12, 8996').

Figure 9. Pyritization. Thin layers of very fine-grained pyrite parallel to the stratification in an off-reef shale sample, X0.7 (Location, 6-32-61-11, 8643').

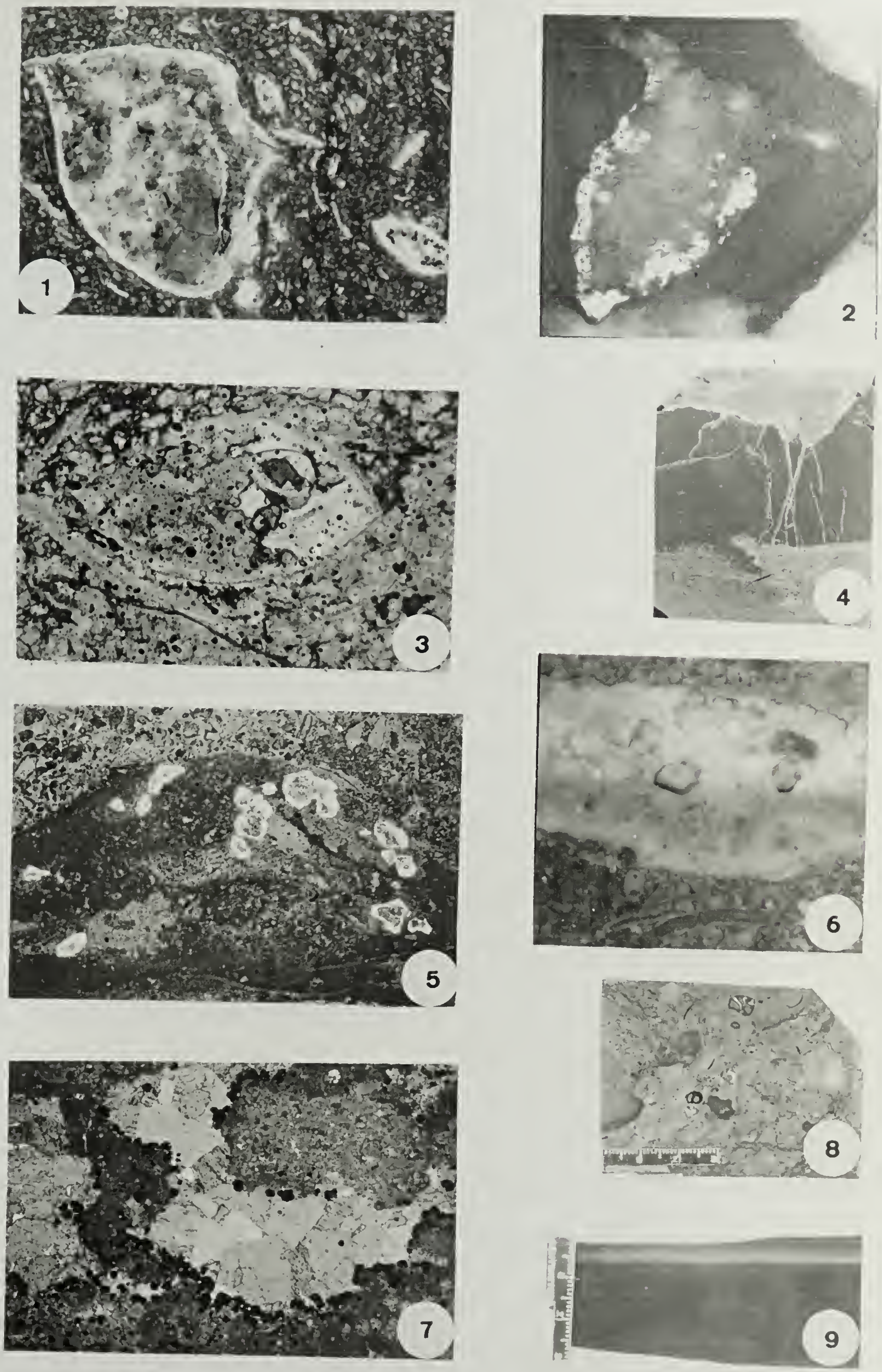


PLATE XXI

Pyrite:

Pyrite is a common accessory mineral and has several modes of occurrence in the limestones of this study. Though present in all rock types it is characteristic of the darker, argillaceous, and more bituminous rocks. The following types of pyrite have been found: finely crystalline pyrite disseminated through the rocks, replacement of fossils, pyrite associated with stylolites, lining vugs or fractures, concentrated at the top of the reef complex, and concentrated in layers that are approximately parallel to the bedding. The various forms of pyrite indicate a number of different modes of origin.

The disseminated pyrite is the most common type of occurrence. The small, well-formed, and angular character of these crystals indicates that the pyrite is non-detrital and its close association with voids and original pore space suggests that it formed in many cases early in the diagenetic history of the rock before complete cementation and lithification.

Pyrite replacing fossils is a common feature especially in the off-reef, reef platform, and deep fore-reef limestones. Here the pyrite usually replaces the entire fossil material but preserves its original shape and character (Plate XXI, Figure 8). Brachiopod shells appear to be the most susceptible to pyritization but gastropods, ostracodes, and tentaculids are also commonly replaced. Rounded masses of micritic sediment often occur in the back-reef rocks that differ from the surrounding limestone by their different color and abundance of pyrite. These are interpreted as being largely algal-balls in which decomposition of the algal material and bacterial activity caused the formation of the abundant, very fine-grained pyrite.

Along with other insoluble minerals, pyrite is found concentrated along stylolite seams. This pyrite is believed to have formed before the pressure solution occurred and is thus only a residue mineral left after the carbonates were dissolved. Part of it however, may represent precipitation from solutions either during or after the process of stylolitization.

Pyrite is also occasionally found lining vugs or cavities (Plate XXI, Figure 7). After the deposition of the pyrite the vugs were filled with sparry calcite and dolomite. This type of pyrite is unquestionably a relatively early diagenetic precipitate, being deposited on the cavity wells before the voids were filled with calcite cement or compressed through compaction. Biological activity may have played an important part in the formation of this type of pyrite.

An interesting occurrence of pyrite is its concentration at the uppermost surface of the reef complex where it is overlain by the argillaceous limestones and shales of the Waterways Formation (Plate XXII, Figure 1). Available evidence indicates that the top of the reef complex is an erosional surface or represents a small local unconformity. The concentration of pyrite at this surface strengthens this view since pyrite is commonly associated with unconfomities. The nature of the pyrite, forming a sharp contact with the overlying shales and an irregular or gradational contact with the underlying limestones is also similar to that found at unconformities. Additional evidence that indicates the pyrite formed at the top of the reef complex before the overlying shales were laid down is its presence as small, rounded, pyrite nodules projecting slightly above the surrounding limestone subsurface. This phenonmenon could be the result of the pyrite being more resistant to erosion and solution than

the surrounding limestone. Though the major part is believed to be a result of the erosional nature of the reef top; the pyrite may also have formed from an upward migration of H_2S through the more porous reef complex during diagenesis. This upward migration of the H_2S would be halted at the top of the reef complex by the impermeable Waterways Formation and might result in the precipitation of pyrite at that locality. Though this is theoretically possible, there is no direct evidence that any of the pyrite formed in this manner.

In some of the off-reef sediments thin layers and lenses of pyrite occur that are approximately parallel to the bedding or stratification (Plate XXI, Figure 9). Some of this may be detrital but its very fine-grained size and its presence in the dark, bituminous, argillaceous limestones suggests that it is probably either a chemically- or biologically-activated pyrite precipitate deposited during sedimentation.

Solution and Fracturing

Evidence of post-depositional solution can readily be found within the rocks of the Carson Creek North reef complex. The following features are briefly discussed to illustrate this phenomenon: stylolites, microstylolitic grain contacts, and secondary vugs or voids.

Stylolites are well developed in the Carson Creek North beds, especially in the more argillaceous or carbonaceous limestones. The stylolites vary in color from green to light brown to black, and in appearance from thin vertically striated columns of considerable height, to branching types, to planar laminae with little or no relief.

The origin of stylolites is not discussed here in any detail but it should be pointed out that although the evidence from the present study indicates that the majority formed through processes of pressure, solution, and removal of soluble material, stylolites probably have more than one mode of origin. Some stylolitic layers may be argillaceous or bituminous depositional laminae that mark a brief hiatus or break in the normal carbonate deposition. These thin detrital layers could be compacted during early diagenesis providing planes for movement and flow without any actual solution of the surrounding carbonate. Some of the stylolitic layers that show no evidence of solution could have originated in this way. Also, some of the stylolitic layers found in the present study could very well represent deposits of thick algal-mat layers or other soft-bodied organisms that on burial provided thin irregular layers composed largely of carbonaceous matter and pyrite. Compaction of this layer could then form the characteristic stylolitic-looking insoluble seam. As stated previously, however, the majority of the stylolites found are associated with solution of both micrite and allochems. Plate XXII, Figure 4 illustrates very well the solution of Amphipora fragments and matrix and shows the initial stages in stylolite formation. Numerous small stylolites can be seen especially at the grain contacts. In this example the process was stopped for some reason and the secondary voids are filled with clear calcite spar. Plate XXII, Figure 3 shows microstylolites between interlocking Amphipora fragments. Though not common in most of the reef complex limestones, microstylolitic grain contacts are rather common in the Amphipora limestones of the reef platform facies. The presence of displaced and transected fossils and allochems at stylolite boundaries is evidence of the solution that occurred during formation. Stylolites are in general considered to be a relatively late diagenetic effect. For a more complete review on stylolite formation the reader is

PLATE XXII

Solution and Fracturing

Figure 1. Reef contact. Hand specimen showing the erosional contact between the reef complex and the overlying argillaceous limestone. Note the abundance of pyrite and how the contact cuts a stromatoporoid fragment, X0.7 (Location, 16-31-61-11, 8539').

Figure 2. Internal sediment. Thin section (crossed nicols) showing three distinct layers of internal sediment and equant and fringing calcite cement, X9 (Location, 6-36-61-12, 8480').

Figure 3. Stylolitic contacts. Thin section showing compressed *Amphipora* stems that have microstylolitic contacts, X9 (Location, 16-5-62-11, 8646').

Figure 4. Solution. Polished section showing solution of matrix and *Amphipora* grains, and the beginning of stylolite formation, X8 (Location, 16-5-62-11, 8645').

Figure 5. Vuggy porosity. Thin section showing indiscriminate vuggy solution of a calcarenite, X9 (Location, 16-31-61-11, 8544').

Figure 6. Solution. Hand specimen showing a cream colored, *Stachyodes*, micritic limestone in which much of the groundmass has been removed and the spaces filled with fringing calcite cement and dark internal sediment. This was later followed by erosion and deposition of an algal-stromatoporoid matt over the rock (see top of photograph), X0.75 (Location, 16-6-62-11, 8826').

Figure 7. Solution. Magnification of Figure 6 showing the fringing calcite cement, X6

Figure 8. Fracturing. Peel (negative photograph) showing a late diagenetic fracture filled with calcite and bitumen, X0.8 (Location, 6-11-62-12, 8900').

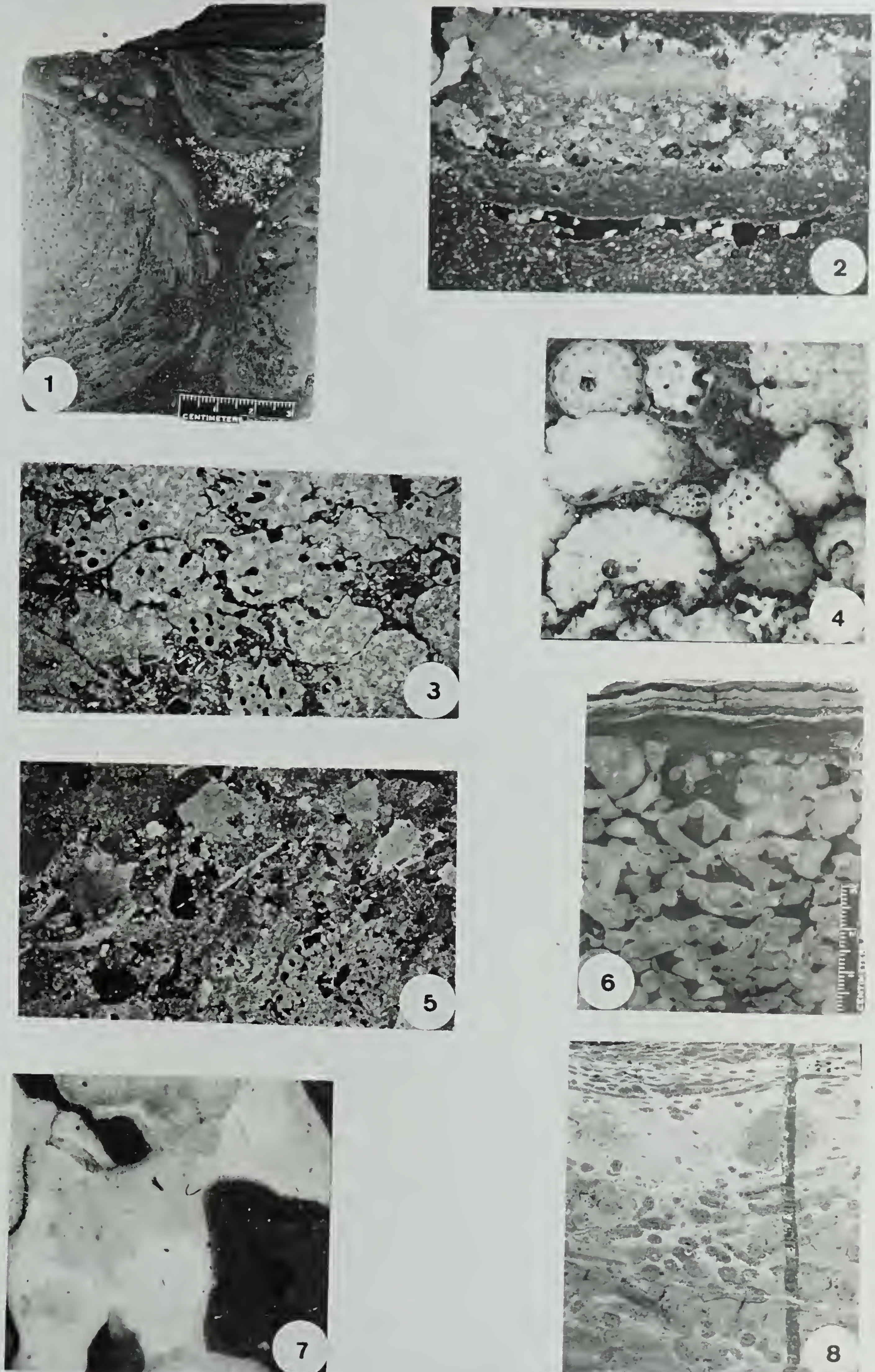


PLATE XXII.

referred to Stockdale (1922), Shaub (1939), Dunnington (1954), and Jenik (1965).

Besides stylolites and microstylolites, secondary voids or openings are evidence of diagenetic solution within the reef complex limestones. Selective solution of grains in which part or all the allochem is dissolved is not a common feature of the Carson Creek North limestones but has been seen on occasion. More common is the indiscriminate vuggy solution in which the micrite or intergranular cement is leached as well as part of the surrounding grains and fossils (Plate XXII, Figure 5). This type of solution is most characteristic of the reef and fore-reef rocks, especially the skeletal calcarenites. Plate XXII, Figures 6 and 7 show a number of diagenetic (?) processes one of which appears to be solution, probably subaerial solution. Originally the sediment consisted of a partially or wholly consolidated light brownish grey micrite containing numerous Stachyodes fragments. This sediment is then believed to have been partially dissolved during which time most of the light micritic matrix was leached away. This probably occurred during subaerial exposure. This was followed respectively by deposition of fringing calcite cement on the walls of the newly formed cavities and channels; deposition of dark brown clastic sediment within the cavities; deposition of equant sparry calcite in the remaining pore space; erosion of the upper surface; and finally deposition of an algal-stromatoporoid layer on top of this erosion surface.

Fractures are generally not very abundant in the reef complex limestones and are most evident in the finer-grained back-reef facies. They appear to be randomly oriented and probably represent several different periods of formation. Some appear to be confined to only certain nodules or layers and stop at adjacent depositional

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layers or structures. These are commonly filled with the surrounding sediment and are believed to be early diagenetic fractures formed during deposition, early compaction, or subaerial exposure. The more common type of fractures found, however, tend to be longer and cut all the other textural components. These in general are believed to be post-lithification features and probably represent several generations of formation. Most are filled with sparry calcite with some dolomite, pyrite, and/or organic matter present. Some are uncemented and thus provide good porosity. These fractures and the secondary vugs provide the secondary porosity found in the Carson Creek North field, while the more important primary porosity is largely intergranular and intra-skeletal.

A paragenetic sequence or inferred time relationship for the various diagenetic features has not been attempted here since much more detailed work on the inter-relations of the various parameters is needed before any definite conclusions can be reached. In general, however, evidence from the study indicates that biological diagenesis, fibrous calcite cementation, much of the equant calcite cementation, internal mechanical deposition, pyrite formation, and much of the compaction and lithification occurred during a relatively early period in the diagenetic history of the rocks. On the other hand, the majority of the neomorphic changes, dolomitization, silification, fracturing, and fracture-filling with cement are believed to be relatively late diagenetic features.

CHAPTER 9 - DEVELOPMENT OF THE CARSON CREEK NORTH REEF COMPLEX

Interpretation of the stratigraphic, paleontologic, and petrographic data allows a simplified version of the depositional history of the reef complex to be reconstructed. The depositional sequence can be divided into six major stages as shown in Figure 23. These postulated major stages are believed to represent only the most important changes that occurred during reef growth, such as those caused by significant changes in sea level or environment. These features tend to be marked in the rocks by distinct changes in the lithology and fossil content. The interpretation of the events concerned with the various stages in the reef complex development are as follows:

Stage 1. Platform Development

The deposition of the Dark Brown Member, or reef platform, is believed to represent the initial transgressive phase of the Upper Devonian seas. Prior to this transgression the study area had been subjected to considerable uplift, regression, and fluctuating conditions as evidenced by the detrital and evaporitic nature of the underlying Middle Devonian rocks. This initial transgression is believed to have been relatively mild and associated with long stable periods, as the rocks deposited in the study area are of a biostromal nature. The lack of major facies changes, the shallow-water carbonate nature of the deposits, and the lateral rather than vertical growth of the reef patches, indicates that this transgressive phase took place under relatively stable conditions. Dark, bituminous, fine-grained limestones containing abundant *Amphipora* characterize the reef platform sediments.

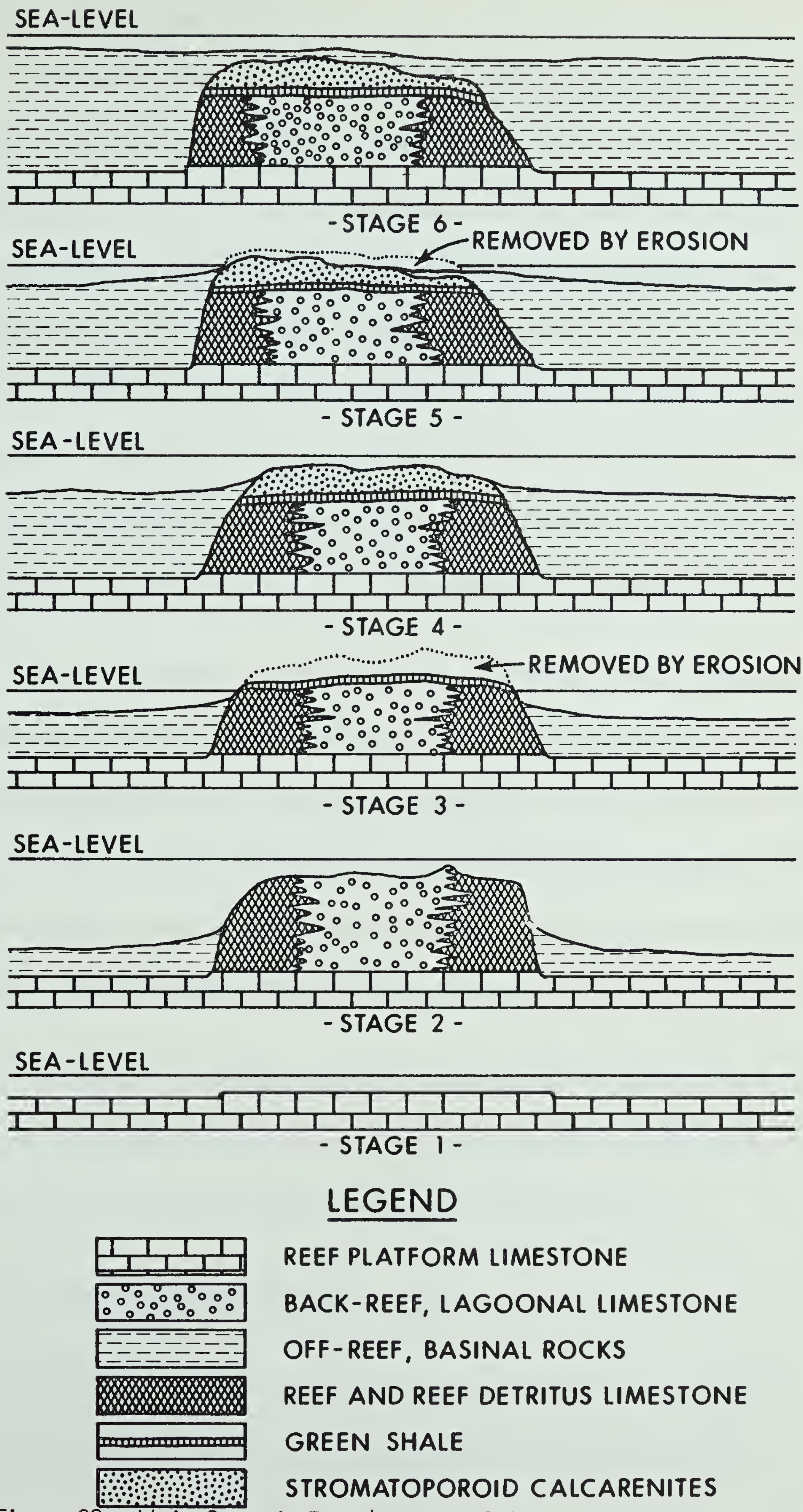

Figure 23. Main Stage in Development of the Carson Creeck North Reef Complex (not to scale)

Stage 2. Bioherm Development

The second stage is represented by the lower two-thirds of the Swan Hills reef complex or Light Brown Member. During this time an atoll-like buildup with its lateral zonation of reef complex facies developed on top of the reef platform. There does not appear to have been any break in sedimentation between Stages 1 and 2, and the change from platform to reef complex was transitional. The biohermal reef complexes are believed to have formed on highs or more positive areas of the underlying platform during this period. This stage represents a period of greater water depth and more extensive transgression than Stage 1, as evidenced by the development of bioherms and basin deposits rather than widespread shelf or platform limestones.

Within this major transgressive stage, evidence of minor transgressive and regressive oscillation can readily be found. Thin, green shale beds and intraformational conglomerates indicate periods of brief emergence within this phase of reef growth. The available evidence indicates that there was probably considerable relief between the reef complex and the basin during this stage, and the various reef complexes in the area were separated by deep, narrow channels.

The present thickness of the rock representing this stage is believed to be much less than that originally deposited. A period of extensive uplift and erosion is believed to have removed considerable limestone during Stage 3.

Stage 3. Green Shale Development

Following the major transgressive phase of Stage 2 was a period of uplift or regression of the sea that resulted in considerable erosion and solution of the exposed

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reef complex. This period is represented by the green shale microfacies that consists of residual green shale, limestone breccias, and supratidal algal-flat deposits. The average thickness of the green shale found is about one foot. Most of the limestones of the reef complex contain about 0.5 to 1.0 per cent insoluble material; thus if the green shale is largely residual material left after solution and erosion, then 50 to 100 feet of reef carbonate was removed during Stage 3.

It is also believed that during this period of reef complex erosion, the off-reef areas were receiving increased sedimentation due to the shallowness of the water and the increase in supply from the surrounding exposed areas. It is suggested that during this period, the thickness of the off-reef sediments nearly caught up to that of the reef complex, and by the end of Stage 3 only minor relief remained between the reef complex and off-reef areas.

Stage 4. Stromatoporoid - Calcarenite Bank Development

The final depositional phase in the history of the Carson Creek North reef complex resulted in the formation of a porous calcarenite - reef detritus unit that covers most of the buildup. This unit is believed to represent deposition in very clear, shallow-water where reef-building organisms thrived but their fossil remains were broken-up and transported to form a bioclastic deposit. This type of deposit is similar to many of the bank or shallow-shelf carbonate deposits forming today. The coarse, clean, fragmental nature of these rocks and the abundance of stromatoporoid and coral fragments suggests a well-aerated, shallow-water environment of deposition. It is suggested that this unit was laid down under relatively stable conditions with only minor relief between it and the basinal areas. A period of emergenge and erosion

is believed to have terminated the development of this unit and the reef complex.

Stage 5. Termination of Reef Complex Growth

The upper boundary of the reef complex is marked by either a thin reef-rubble zone or a sharp erosional contact with the overlying argillaceous limestones. Also, the upper contact is characterized everywhere by a marked pyrite concentration. The reef-rubble zone is interpreted to have formed in shallow pools and partially exposed portions of the back-reef area during periods of brief emergence. The rim areas of the reef complex tend to have a sharp, erosional surface at the upper contact rather than the more transitional reef rubble zone (see Plate XXII, Figure 1) and may represent either subaerial or submarine erosion. The fact that the material was lithified before or during the erosion, however, suggests that these areas may have been subjected to at least brief periods of emergence. The terracing of the eastern edge of the complex is also associated with this erosive phase. The lack of green shale beds and stylolites at this upper reef contact suggests that the erosion, whether it took place above or below water, was largely physical or mechanical rather than chemical.

It is thus suggested that the death or termination of growth of the Carson Creek North reef complex was caused by a shallowing rather than a deepening of the water. The erosion associated with this period and the time involved, allowed the off-reef areas to be filled with sediments to the point that practically all relief between the reef complex and basinal areas was removed. This accounts, in part, for the lack of draping of the shales and argillaceous limestones of the Waterways Formation over the reef complex.

Stage 6. Waterways Development

Following the period of regression and erosion that marks the end of reef growth, there was a period of transgression and deepening of water. This period resulted in the deposition of the argillaceous limestones and shales throughout the area under study that cover the reef complexes as well as the basin areas. The rapid deepening of the water during this period, the muddiness of the water, and, to a lesser extent, the lack of relief between reef and off-reef areas are believed to be the principal reasons why reef growth did not again start at this time.

CHAPTER 10 - SUMMARY AND CONCLUSIONS

1. Carson Creek North is a small, oval-shaped, biohermal reef complex that occurs in the subsurface of Alberta about 100 miles northwest of the city of Edmonton.

2. The age and lateral equivalents of the Beaverhill Lake Group have not been definitely established. The available evidence, however, indicates that most of the Beaverhill Lake Group is early Upper Devonian in age, although the Dark Brown Member and the Fort Vermilian Formation may be of late Middle Devonian age. The Waterways, Souris River, Slave Point, Fort Simpson, Hay River, and Flume Formations are believed to be the lateral equivalents of the Beaverhill Lake Group.

3. It is suggested that the following terminology be adapted in the areas of west-central Alberta where the Swan Hills carbonates are recognizable: Beaverhill Lake Group (overall assemblage of reef, reef platform, and basinal rocks); Waterways Formation (argillaceous basin or off-reef facies); Swan Hills Formation (reef complexes and reef platform); Light Brown Member (Swan Hills reef complex); Dark Brown Member (Swan Hills reef platform); and Fort Vermilion Formation (thin basal anhydrite overlying the Elk Point Shale).

4. The Beaverhill Lake deposits represent the initial phase of the extensive Upper Devonian transgression. The resulting sediments were deposited in the pattern of shale basin - platform edge - reef complex - shallow water shelf facies configuration, going from north to south in the Western Canada Sedimentary Basin. The general transgressive period was interupted by numerous periods of stillstand and regression.

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5. The Swan Hills reef complexes appear to have largely formed on pre-existing reef-platform highs.

6. The present topographic profile of the reef complex is believed largely due to erosion, solution, and non-reefal sedimentation and therefore cannot be used to reconstruct the profile present during active reef growth.

7. Correlation between reef and off-reef sections is difficult because of the lack of traceable markers both on logs and in the lithology. There does not, however, appear to be any draping of the off-reef sediments over the reef complex.

8. The green shale beds are believed to be largely residual deposits left after parts of the reef complex became emergent and were subjected to considerable erosion and solution. All the features associated with the green shales are of a subaerial or very shallow-water character rather than of a deeper-water nature like those of the dark off-reef shales.

9. The top of the reef complex is marked by either a reef-rubble zone (back-reef areas) or an erosional surface (fore-reef areas) and by a marked concentration of pyrite. Thus, the upper boundary is largely an erosional feature or unconformity (both subaerial and submarine) and the death of the reef organisms was due to emergence or shallowing of the water rather than submergence or deepening. The brief period of emergence that terminated reef growth was then followed by submergence and deposition of the argillaceous sediments over the reef complex.

10. Stromatoporoids are the most abundant fossils found, and were the principal reef builders, in the Carson Creek North reef complex. The shape and size of the coenostea are believed to be as important as specific identifications for environmental studies since individuals often assumed a variety of shapes depending upon the environment in which they were growing.

11. Algae are believed to have been far more important in the development of the Swan Hills reef complexes than previously recognized. Abrasion, alteration, and recrystallization of algae to form micrite; binding and encrusting of both loose sediment and the organic-reef framework; boring, corrosion, and alteration of skeletal particles; lithification; formation of small reef patches on the fore-reef slope; and formation of algal-laminated sediments in the intertidal and supratidal areas are some of the contributions of algae to the evolution of the reef complex as recognized in this study.

12. A lateral zonation of organisms across the reef complex allows the reef, fore-reef, and back-reef facies to be distinguished and enables the reef complex to be divided into biosomes or intertonguing biostratigraphic units. In general, the fore-reef rocks are characterized by tabular stromatoporoids, brachiopods, *Stachyodes*, solenoporoid algae, and crinoids; the reef facies by massive stromatoporoids, *Stachyodes*, brachiopods, corals, tabular stromatoporoids, and crinoids; while *Amphipora*, calcispheres, ostracodes, foraminifera, and non-calcareous algae are the most common constituents of the back-reef areas.

13. Petrographic and paleontologic data permit subdivision of the reef complex

into a number of facies, microfacies, and rock types. In the Carson Creek North field the rocks were divided into 5 facies, 11 microfacies, and 32 rock types. In general the off-reef rocks are fine grained, argillaceous, dark-colored, and poorly fossiliferous; the reef platform rocks are dark colored, micritic, dense and contain abundant Amphipora; the fore-reef rocks are fragmental, moderately coarse, and light colored; the reef rocks are light colored, skeletal, coarse-grained, non-bedded, and porous; while the back-reef rocks tend to be fine-grained, dense, bedded, and contain abundant Amphipora.

14. The organic-reef has been found preserved in growth position in a few wells but forms an insignificant part of the reef complex volumetrically. During active reef growth, however, it is believed to have been more prominent and supplied vast quantities of sediment to the back-reef and fore-reef areas. It also gave considerable protection to the back-reef environment from the erosive action of the incoming waves and currents.

15. Geochemical data obtained from both whole rock and acid-soluble analyses is believed to be of considerable importance in reef complex studies by helping to: differentiate facies, interpret environmental conditions, and to outline the reef profile. The greater the number of elements that can be quantitatively analysed for, and the more samples studied, the more useful will be the resulting information.

16. The present study showed that the off-reef samples are generally much higher in Sr, Mg, Mn, Fe, S, Si, and Al and much lower in Ca than the reef- complex samples. Within the reef-complex facies: Sr, Mg, Mn, Fe, and Si tend to be

concentrated in the fore-reef position; Sr and Ca in the reef rocks; and Ni, Al, and Si tend to be high in the back-reef areas. Most of the geochemical variations between facies are believed to be real and to be the result of the physical variables of the depositional area and post-deposition changes, rather than due to any chemical variables in the depositional environment.

17. Diagenetic changes are common in the Carson Creek North limestones but in general the original textures and structures are not obliterated. Although hard to distinguish, biological diagenesis is believed to have been an important early diagenetic feature. Evidence for compaction can be found, though it is believed to have generally not been too severe. Cementation and lithification in many cases were very early diagenetic processes. Neomorphic changes are common features of the Carson Creek North limestones. Algal grain-diminution and the formation of sparry calcite are two of the most common forms of neomorphism observed. Dolomite, silica, and pyrite are the most common authigenic noncarbonate minerals found. Both dolomite and silica replacement are most common in the fore-reef portions of the reef complex while pyrite occurs throughout most rock types. Evidence for post-depositional solution and fracturing is common and provides some porosity in many rock types. Stylolites are a common feature and are believed to have had more than one mode of formation.

18. From a study of the data presented in this paper, six major stages of reef growth and development have been recognized. Within these major periods, evidence for minor oscillations and changes can be found, but lack of data and control does not allow elaboration on these features. The existing evidence indicates that during the major phase of biohermal reef growth considerable relief was present between the

reef and off-reef areas. During the periods of regression and erosion of the complex, this relief was all but removed and by the time the Waterways Formation was deposited over the Carson Creek North field, little or no relief remained between the reef complex and the basinal sediments.

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APPENDIX I

WELLS USED IN THE PRESENT STUDY

The following table lists all the wells used in the present study and gives corrected values for the Beaverhill Lake tops. The corrected values are those found after the regional dip was removed. As pointed out by Klovan (1964), Jenik (1965), and others, removing the regional dip in the construction of structure maps gives a much closer approximation to the original topographic features that were present prior to tilting.

In order to obtain the corrected values, a structure contour map of the base of the Beaverhill Lake Group was constructed. From this map the regional strike in the area was found to be north thirty-five degrees west and the regional dip about forty feet per mile in a south fifty-five degrees west direction. A datum line was then drawn on the structure contour map parallel to the regional strike. Corrected or restored values for all the wells were then obtained by rotating the well depths about the datum line to a horizontal position. These restored values were then used in the construction of the Swan Hills structure contour maps. As also pointed out by Klovan (1964), the value for the original depositional dip of the sediments is unknown, but assuming it to be negligible probably does not introduce any significant error. The following are the subsurface and the corrected subsurface values for all the wells considered in this study.

Table 8.- Wells Used In The Present Study

WELL LOCATION *denotes core slabbed and examined in detail	Kelly Bushing (KB)	Total Depth (TD)	BEAVERHILL LAKE GROUP			SWAN HILLS FORMATION					
						BIOHERMAL BUILDUP			REEF PLATFORM		
			Subsea	Corrected	Thickness	Subsea	Corrected	Thickness	Subsea	Corrected	Thickness
6-18-61-11W5	2915	8955	-5505	-5311	474	-5772	-5578	69	-5841	-5647	138
6-22-61-11W5*	2725	8666	-5367	-5295	474				-5725	-5653	126
6-31-61-11W5	2983	8806	-5432	-5308	391+	-5586	-5462	212	-5798	-5674	35+
16-31-61-11W5*	2917	8739	-5401	-5305	421+	-5627	-5525	127	-5748	-5652	74+
6-32-61-11W5*	2963	8759	-5407	-5316	385+	-5695	-5604	49	-5744	-5653	52+
10-2-61-12W5	2790	8800	-5628	-5332	382+	-5742	-5446	174	-5916	-5620	94+
13-12-61-12W5	2898	9343	-5557	-5309	480	-5711	-5463	191	-5902	-5654	135
10-20-61-12W5	2772	8990	-5672	-5352	442	-5716	-5396	272	-5988	-5668	126
7-22-61-12W5	2751	8720	-5633	-5373	336+	-5697	-5437	228	-5925	-5665	44+
7-24-61-12W5	2825	8740	-5519	-5321	397+	-5744	-5546	86	-5830	-5632	85+
16-26-61-12W5*	2881	8807	-5559	-5375	367+	-5847	-5663	17	-5864	-5680	62+
7-28-61-12W5*	2773	8762	-5627	-5355	362+	-5673	-5401	259	-5932	-5660	57+
10-31-61-12W5	2957	9005	-5651	-5355	397+	-5701	-5405	324	-6025	-5729	23+
16-32-61-12W5	2945	8953	-5628	-5368	380+	-5873	-5613	67	-5940	-5680	68+

Table 8. - continued

WELL LOCATION	KB	TD	BEAVERHILL LAKE GROUP			SWAN HILLS FORMATION					
						BIOHERMAL BUILDUP			REEF PLATFORM		
			Subsea	Corrected	Thickness	Subsea	Corrected	Thickness	Subsea	Corrected	Thickness
16-33-61-12W5*	2766	8745	-5576	-5348	403+	-5630	-5402	276	-5906	-5678	73+
16-34-61-12W5	3046	8960	-5526	-5331	388+	-5588	-5393	258	-5846	-5651	68+
6-35-61-12W5	3055	8930	-5525	-5335	350+	-5619	-5429	245	-5864	-5674	11+
16-35-61-12W5	3011	8898	-5493	-5330	394+	-5573	-5410	255	-5828	-5665	59+
6-36-61-12W5 *	2863	8740	-5477	-5319	400+	-5575	-5417	259	-5834	-5676	43+
16-36-61-12W5	2994	8840	-5451	-5321	395+	-5565	-5435	223	-5788	-5658	58+
10-36-61-13W5	2722	8900	-5678	-5338	463	-5732	-5392	324	-6056	-5716	85
13-2-62-11W5	2987	8943	-5243	-5277					-5603	-5637	
6-5-62-11W5	2975	8720	-5363	-5297	382+	-5603	-5537	100	-5703	-5637	42+
16-5-62-11W5*	2925	8688	-5348	-5308	415+				-5683	-5643	80 +
6-6-62-11W5	3088	8912	-5409	-5315	415+	-5540	-5446	206	-5752	-5652	78+
16-6-62-11W5*	3121	8968	-5372	-5298	457	-5565	-5491	149	-5714	-5640	115
6-7-62-11W5	3209	8992	-5379	-5301	404+	-5625	-5547	100	-5725	-5647	58+
16-7-62-11W5	3124	9050	-5366	-5316	492				-5598	-5548	

Table 8. - continued

WELL LOCATION	KB	TD	BEAVERHILL LAKE GROUP			SWAN HILLS FORMATION					
						BIOHERMAL BUILDUP			REEF PLATFORM		
			Subsea	Corrected	Thickness	Subsea	Corrected	Thickness	Subsea	Corrected	Thickness
6-8-62-11W5	3138	8955	-5363	-5320	454+						
10-15-62-11W5	3098	8922	-5237	-5299	490				-5592	-5654	135
10-29-62-11W5	3405	9231	-5250	-5288	487	-5433	-5471	200	-5633	-5671	104
2-31-62-11W5	3558	9278	-5269	-5287	451+	-5377	-5395	307	-5684	-5702	36+
10-34-62-11W5	3309	9015	-5143	-5269	493	-5489	-5615	51	-5540	-5666	96
6-1-62-12W5*	3203	9245	-5461	-5326	466	-5552	-5417	243	-5795	-5660	132
16-1-62-12W5	3228	9060	-5417	-5311	415+	-5540	-5434	214	-5754	-5648	78+
6-2-62-12W5	3093	9000	-5504	-5338	403+	-5585	-5419	255	-5840	-5674	67+
6-3-62-12W5	2944	8952	-5550	-5350	443	-5603	-5403	271	-5874	-5674	109
16-3-62-12W5	3072	9065	-5512	-5342	448	-5578	-5408	247	-5825	-5655	135
6-4-62-12W5*	2854	8810	-5576	-5344	380+	-5621	-5389	302	-5923	-5691	33+
16-4-62-12W5	2854	8730	-5555	-5351	321+	-5606	-5402	250+			
6-5-62-12W5	3050	9046	-5616	-5352	380+	-5728	-5464	249	-5977	-5713	19+
16-5-62-12W5*	2980	8954	-5603	-5365	371+	-5644	-5406	298	-5942	-5704	32+

Table 8. - continued

WELL LOCATION	KB	TD	BEAVERHILL LAKE GROUP			SWAN HILLS FORMATION: BIOHERMAL BUILDUP			SWAN HILLS FORMATION: REEF PLATFORM		
			Subsea	Corrected	Thickness	Subsea	Corrected	Thickness	Subsea	Corrected	Thickness
16-6-62-12W5	3160	9175	-5608	-5336	407+	-5653	-5381	337	-5990	-5718	25+
6-7-62-12W5*	3243	9275	-5649	-5373	383+	-5762	-5486	165	-5927	-5651	105+
6-8-62-12W5	3060	9024	-5584	-5341	380+	-5633	-5390	322	-5955	-5712	9+
16-8-62-12W5	2912	8872	-5595	-5379	365+	-5768	-5552	160	-5928	-5712	32+
6-9-62-12W5*	2835	8917	-5545	-5337	470	-5593	-5385	309	-5902	-5694	113
16-9-62-12W5	2909	8932	-5517	-5334	454	-5694	-5511	169	-5863	-5680	108
6-10-62-12W5	2971	8803	-5515	-5337	314+	-5576	-5398	256	-5832	-5654	2+
16-10-62-12W5	3104	8930	-5457	-5307	369+	-5545	-5395	271	-5816	-5666	10+
6-11-62-12W5*	3089	8945	-5476	-5333	380+	-5560	-5417	230	-5790	-5647	66+
16-11-62-12W5	3175	9130	-5429	-5313	477	-5553	-5437	166	-5719	-5603	187
6-12-62-12W5	3072	8874	-5411	-5300	391+	-5538	-5427	196	-5734	-5623	68+
16-12-62-12W5	3106	8910	-5399	-5313	405+	-5708	-5622	61	-5769	-5683	35+
4-13-62-12W5	3137	8951	-5427	-5325	387+	-5583	-5481				
6-13-62-12W5	3150	8954	-5394	-5308	410+	-5653	-5567	119	-5772	-5686	32+

Table 8. - continued

WELL LOCATION	KB	TD	BEAVERHILL LAKE GROUP			SWAN HILLS FORMATION					
						BIOHERMAL BUILDUP			REEF PLATFORM		
			Subsea	Corrected	Thickness	Subsea	Corrected	Thickness	Subsea	Corrected	Thickness
6-14-62-12W5	3190	9070	-5450	-5328	430+	-5693	-5571	99	-5792	-5670	88+
6-15-62-12W5	3006	8888	-5468	-5314	414+	-5636	-5482	223	-5859	-5705	23+
4-25-62-12W5	3309	9100	-5357	-5311	434+	-5449	-5393	286	-5735	-5679	56+
8-28-62-12W5	3129	9293	-5440	-5316	476	-5497	-5373	307	-5804	-5680	112
12-36-62-12W5	3371	9100	-5335	-5313	394+	-5389	-5367	316	-5705	-5683	24+
16-13-62-13W5	3273		-5642	-5380	435	-5861	-5599	66	-5929	-5665	150
4-23-62-13W5	3186		-5704	-5396	432	-5820	-5512	184	-6004	-5696	132

APPENDIX II

METHODS USED IN GEOCHEMICAL STUDY

Sampling Procedure:

Samples of the slabbed cores were obtained for the chemical analyses in the following way: A strip about one quarter of an inch in width was removed from every second large piece of slabbed core found in the core boxes. The larger core fragments averaged about 6 inches in length. These consecutive thin core strips were then grouped into composite samples. The actual footage included in the samples varied but generally each represented about 6 feet of core. In all cases no more than one specific rock type was included in any one sample. Only fresh rock was used in the samples with the rough, outside edge of the core being removed with a Dunmore hand grinder using 3/4 inch diamond-studded flat drills. After the sawing and grinding, the core fragments in each sample were thoroughly washed and mixed. The samples were then crushed and homogenized using a Willy Bleuler crusher. Tungsten-carbide grinders were used rather than steel ones to avoid contamination. It was found that three grinding periods, each of 1 minute duration, were sufficient to produce a soft, non-gritty powder fine enough for x-ray determinations. In all stages of the sampling procedure the equipment used was cleaned regularily to avoid contamination.

X-Ray Fluorescence:

The samples ground and mixed in the Willy Bleuler grinder were again thoroughly shaken for one minute to insure homogeneity. Then about 1.5 grams of sample was pressed into an undiluted briquette backed by cellulose. The tablets, having a one-

eighth inch cellulose rim, were made under a pressure of 30,000 p.s.i. Analytical determinations were made for the eight elements on a Phillips Norelco Type 12215/0 unit, using standard x-ray spectrochemical techniques. Strontium was determined using the method of Reynolds (1963). The operating conditions used in the x-ray fluorescence analyses for each element are listed in Table 9. The standards used were of similar composition to the unknown samples to minimize matrix effects and were run under similar x-ray conditions. The calibration curves of the standards used for the various elemental analyses are plotted in Figures 24 to 30.

Table 9. - Operating Conditions for X-Ray Fluorescence Analyses

Element	X-Ray Tube	X-Ray Path	Counter	Counter Voltage	Analysing Crystal	Discriminator Level	Discriminator Window	Peak Position	Background Position
Sr	Mo	Air	Scin.	1600	LiF	1.5	-	25.00°	28.80°
Cr	W	Air	F.P	1500	LiF	5.5	7.0	113.18°	112.00°
Mg	Cr	Vacuum	F.P.	1650	ADP	10.0	12.5	136.55°	135.50°
S	Cr	Vacuum	F.P.	1600	EDDT	11.0	11.0	75.12°	76.00°
Mn	W	Air	F.P.	1440	EDDT	5.0	20.0	62.90°	61.50°
Fe	Mo	Air	F.P.	1600	LiF	1.5	-	57.50°	58.50°
Al	Cr	Vacuum	F.P.	1600	EDDT	6.5	9.5	142.70°	141.50°
Si	Cr	Vacuum	F.P.	1600	EDDT	7.5	10.0	108.00°	107.20°

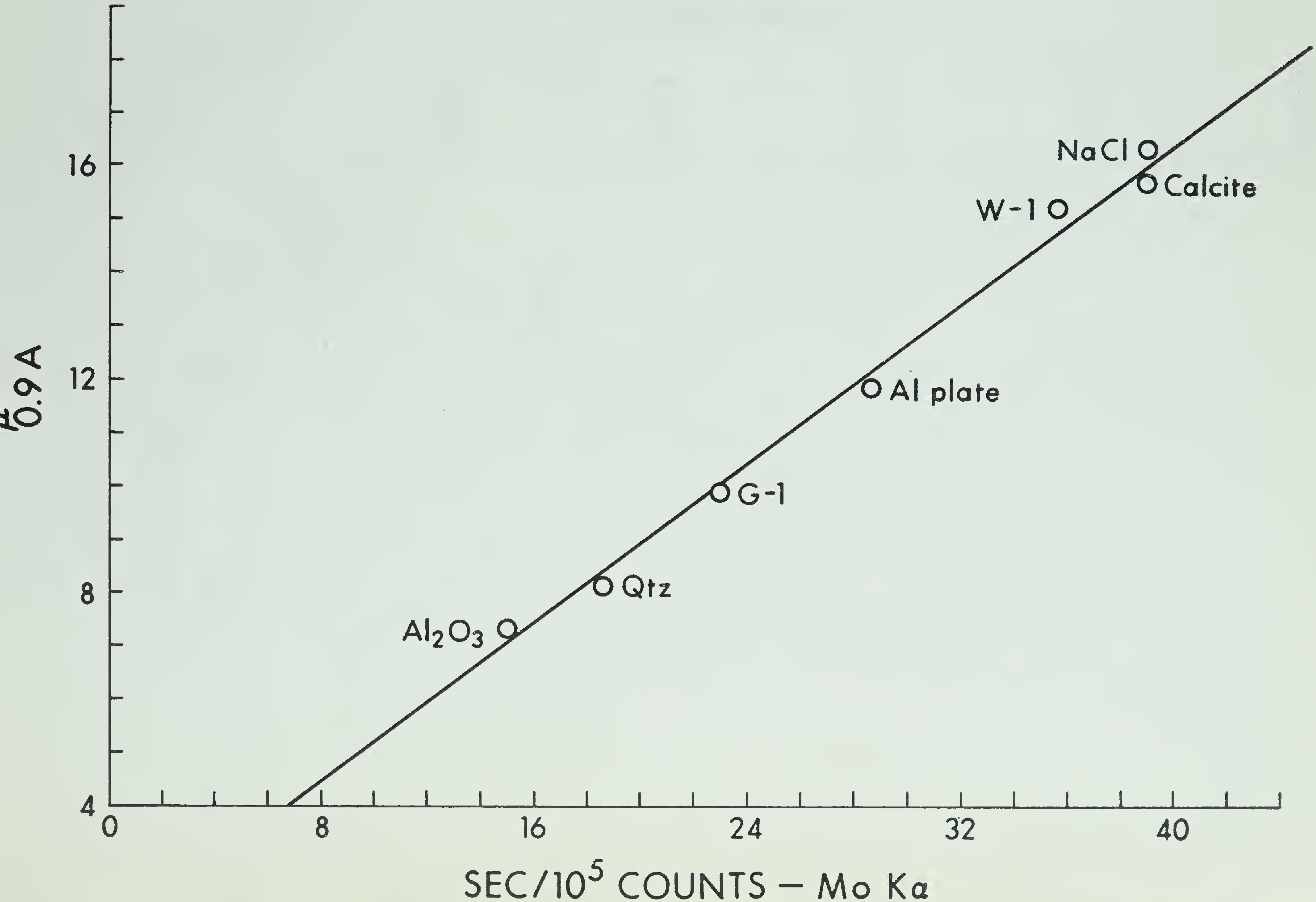

Figure 24. Relation between Compton Scattering and the Mass Absorption Coefficient

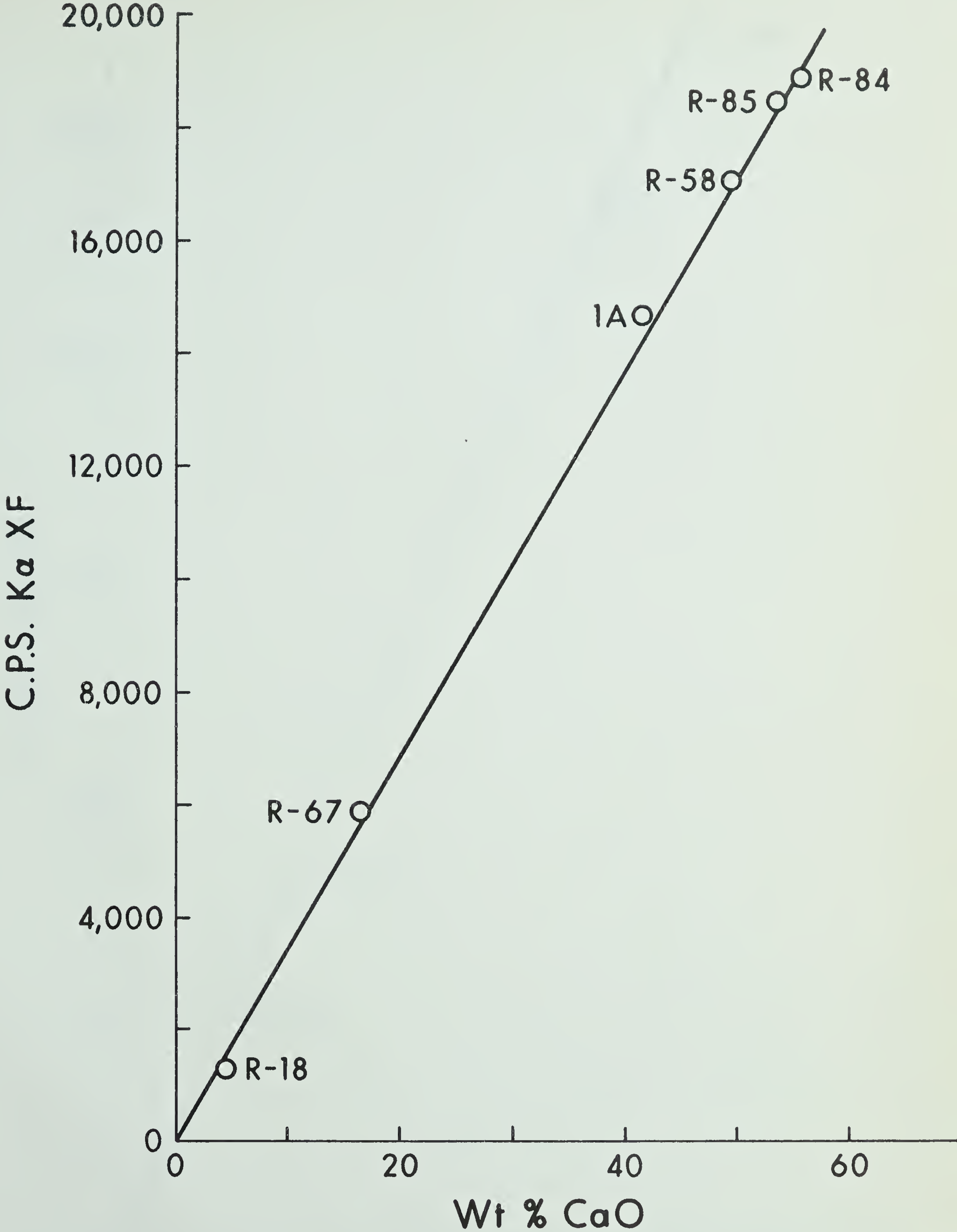

Figure 25. Calibration Curve of standards for CaO

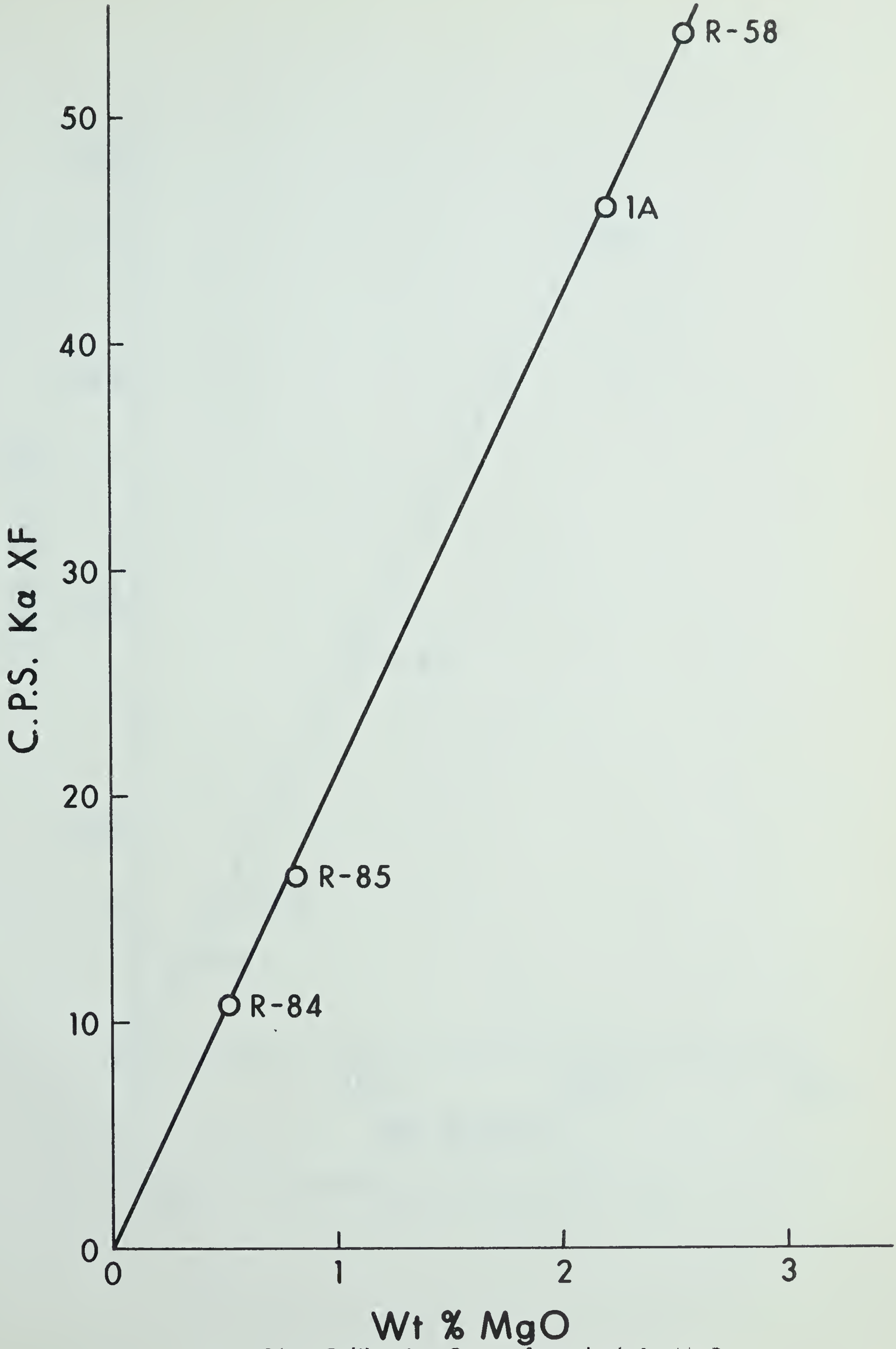

Figure 26. Calibration Curve of standards for MgO

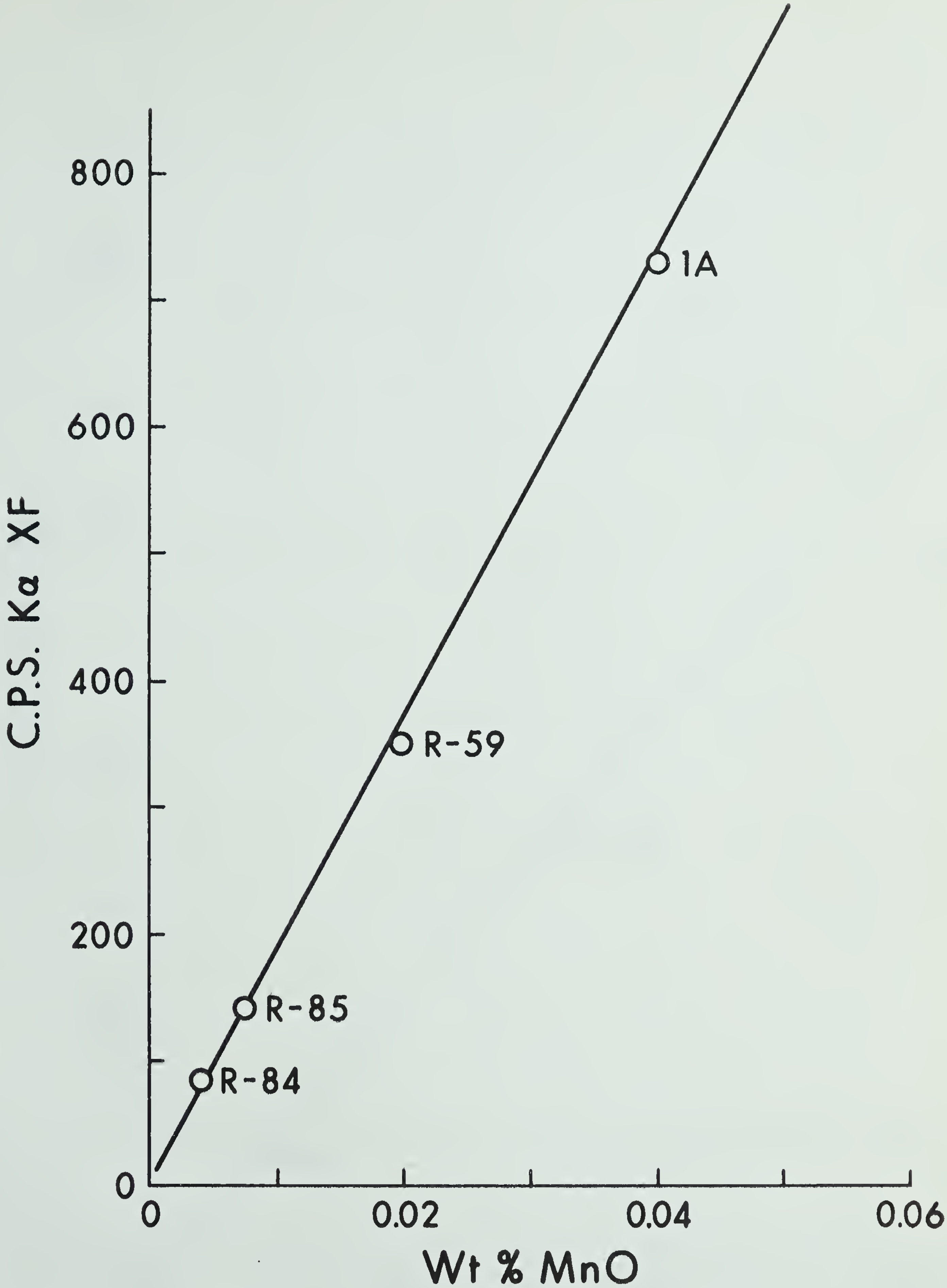

Figure 27. Calibration Curve of standards for MnO

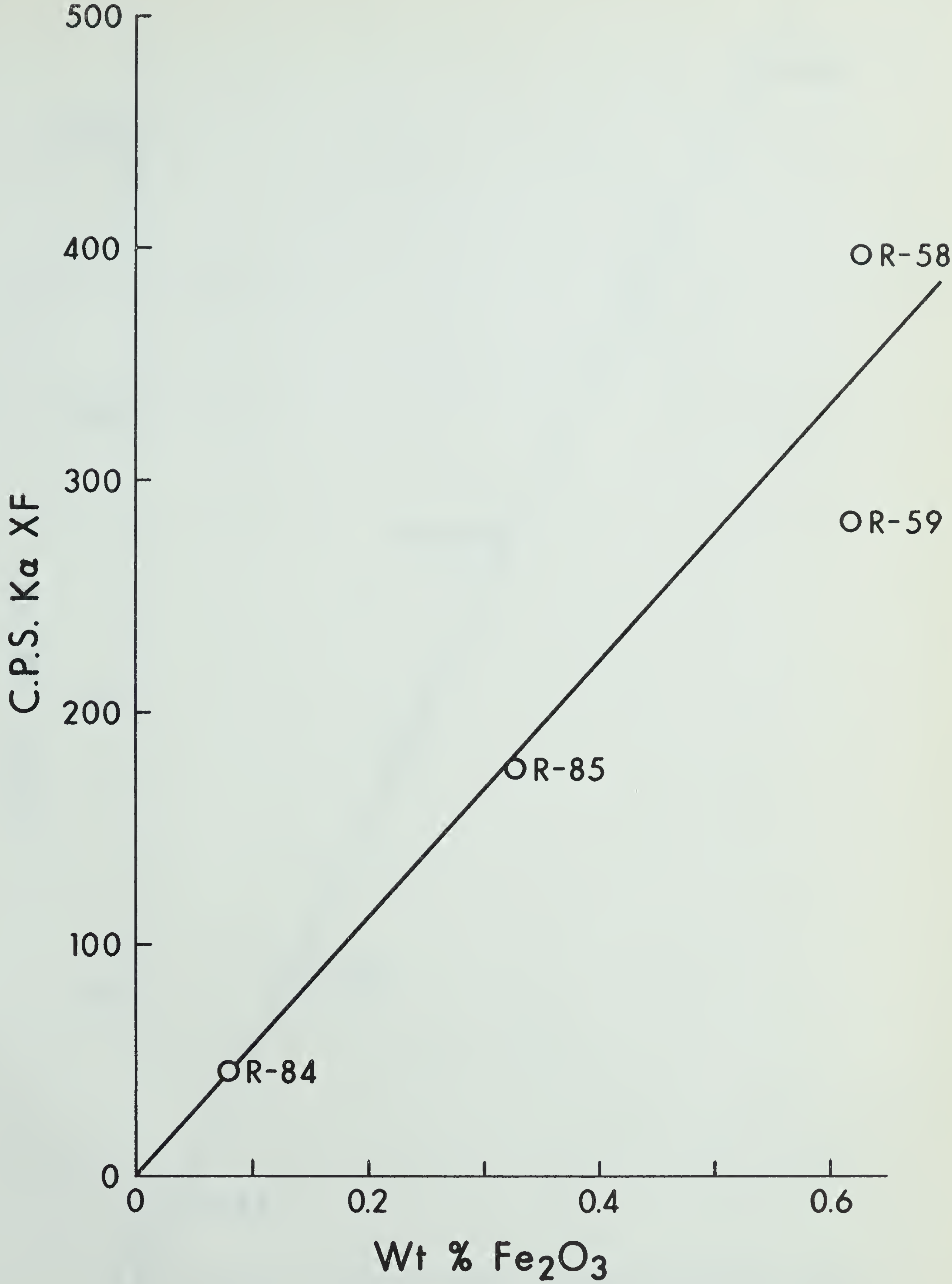

Figure 28. Calibration Curve of standards for Fe_2O_3

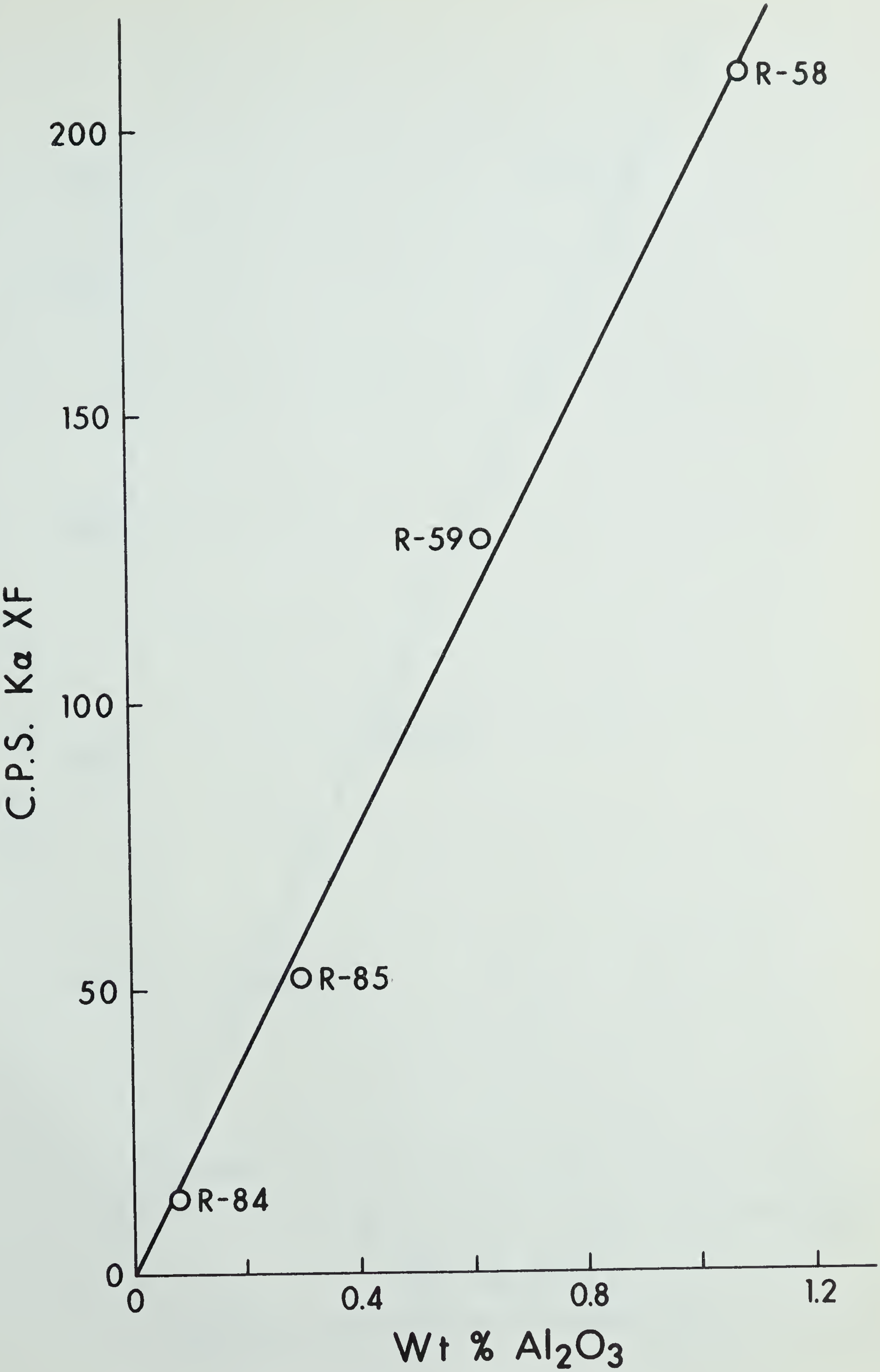

Figure 29. Calibration Curve of standards for Al_2O_3

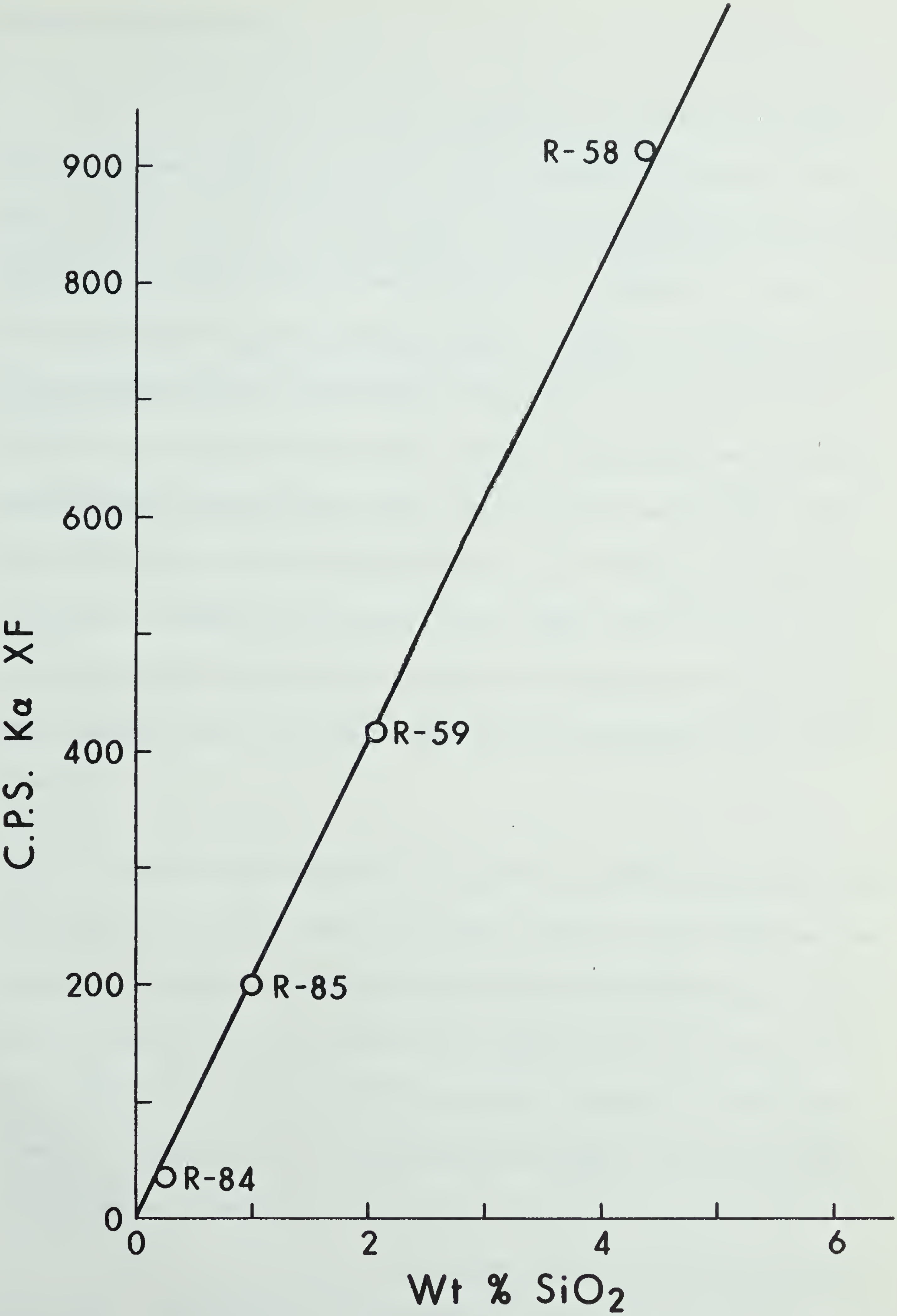

Figure 30. Calibration Curve of standards for SiO_2

Spectrophotometer Analyses:

Forty-one of the samples that were analysed by x-ray fluorescence methods were also analysed by spectrophotometer methods to determine the amount of three elements present in the acid-soluble portion. The procedure followed for these analyses is as follows: Five gram portions of each of the forty-one samples were weighed out to the nearest 0.01 gm. and placed in 150 ml. beakers. About 40 ml. of 30% acetic acid was then added carefully to each beaker. The samples were occasionally stirred and left until all the carbonate was completely dissolved. The solution was then filtered through weighed, blue ribbon filter papers. The precipitate was thoroughly washed and the filter paper and residue dried and weighed. This enabled a close approximation to the amount of insoluble residue present in each sample to be calculated. The solutions were collected in 100 ml. volumetric flasks and diluted up to volume with distilled water. Care was taken in all the above steps to avoid contamination or loss of any of the samples.

Nickle: A standard solution containing 2.11 ppm Ni was made up by diluting analytic $NiCl_2 \cdot 6H_2O$ in a very weak acetic acid solution. Aliquots of this standard solution were then used in the following way to set up a standard calibration curve: Two ml. of the 2.11 ppm Ni solution was pipetted into a separatory funnel. Five ml. of 5% sodium citrate and 10 ml. of acetic acid were added. The solution was then made just basic with NH_3 and 1 ml. of α-Furilodioxime was added. Three, 2 ml. aliquots of chloroform were added and the whole mixture was shaken for at least 1 minute duration after each aliquot addition to insure complete extraction of the Ni complex by the chloroform. The yellowish colored chloroform and Ni complex that separated to

the bottom of the separatory funnel was then drained off and its absorbance value measured on a Beckman Model B colorimetric spectrophotometer. This procedure was then repeated using 1 ml., 3 ml., 4 ml., and 6 ml., aliquots of the Ni solution. This enabled the standard calibration curve plotting absorbance against Ni concentration shown in Figure 31 to be constructed.

The unknown samples were analysed for Ni content in a manner similar to that used for the Ni standards. Ten ml. of unknown sample solution was pipetted into a separatory funnel; 5 ml. of sodium citrate, HNO_3 for basification, 1 ml. of α furilodioxime, and chloroform were added; the mixture was shaken and 10 ml. of the chloroform-nickle complex was then drained off and measured for color absorbance on the colorimetric spectrophotometer. The absorbance values were then converted to micrograms of Ni using the calibration curve. From the micrograms of Ni present in the diluted samples the ppm. Ni present in the acid-soluble portion of the original samples was calculated.

In the analysis the sodium citrate was used to keep any iron from interfering in the reaction. The α furilodioxime was used to complex the Ni, giving a yellow color, and the chloroform was used to collect and extract the Ni complex.

Magnesium: Four standards containing 0.36, 0.60, 1.2 and 2.4 ppm. Mg were made up by diluting analytical $MgSO_4$ in a weak acetic acid solution. These standards were run on a Perkin-Elmer, Model 290 atomic absorption spectrophotometer and the calibration curve shown in Figure 32 was constructed. The following settings were used on the atomic absorption spectrophotometer for both the standards and the unknown analyses:

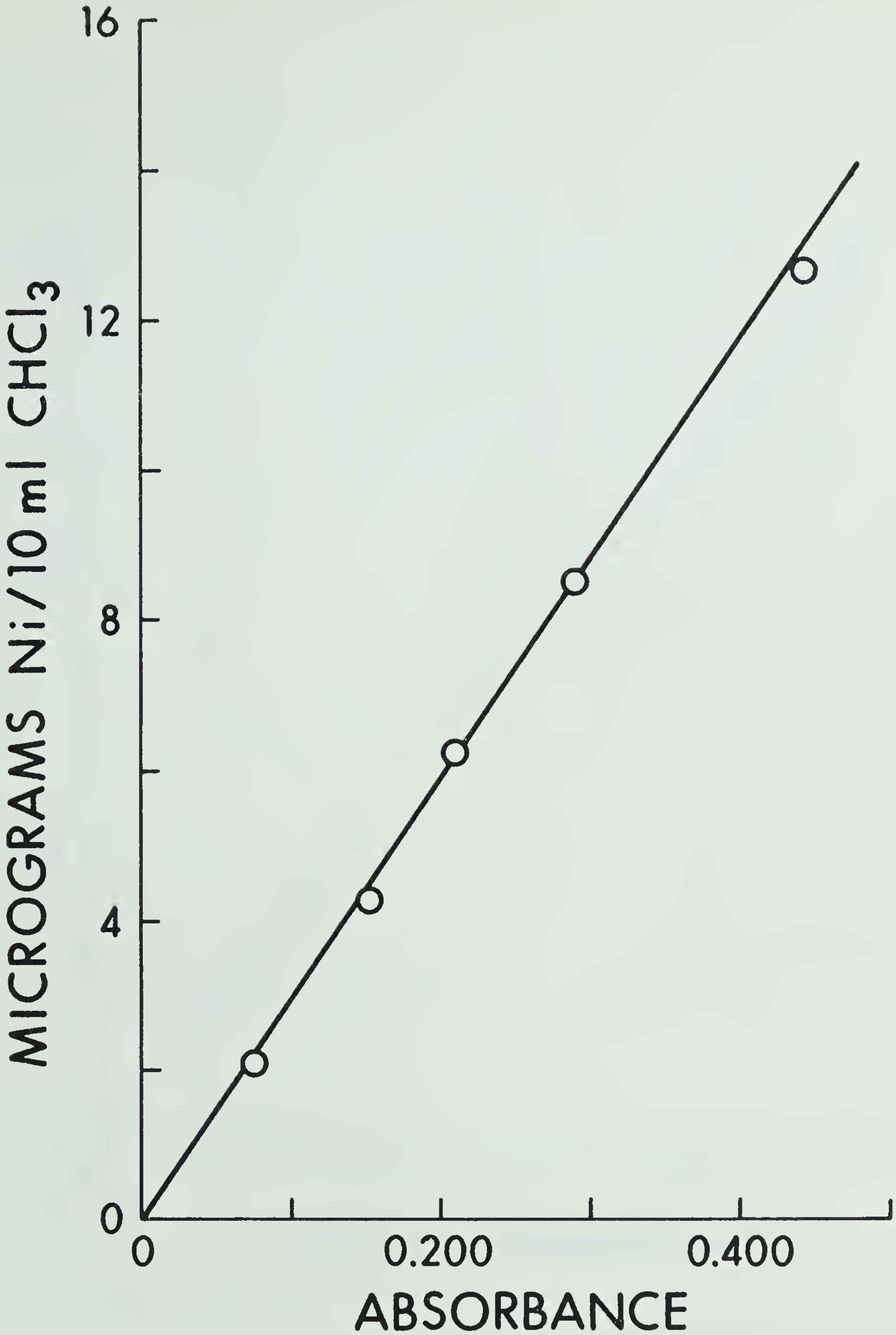

Figure 31. Curve for Conversion from Colorimetric Absorbance Values to Micrograms of Ni

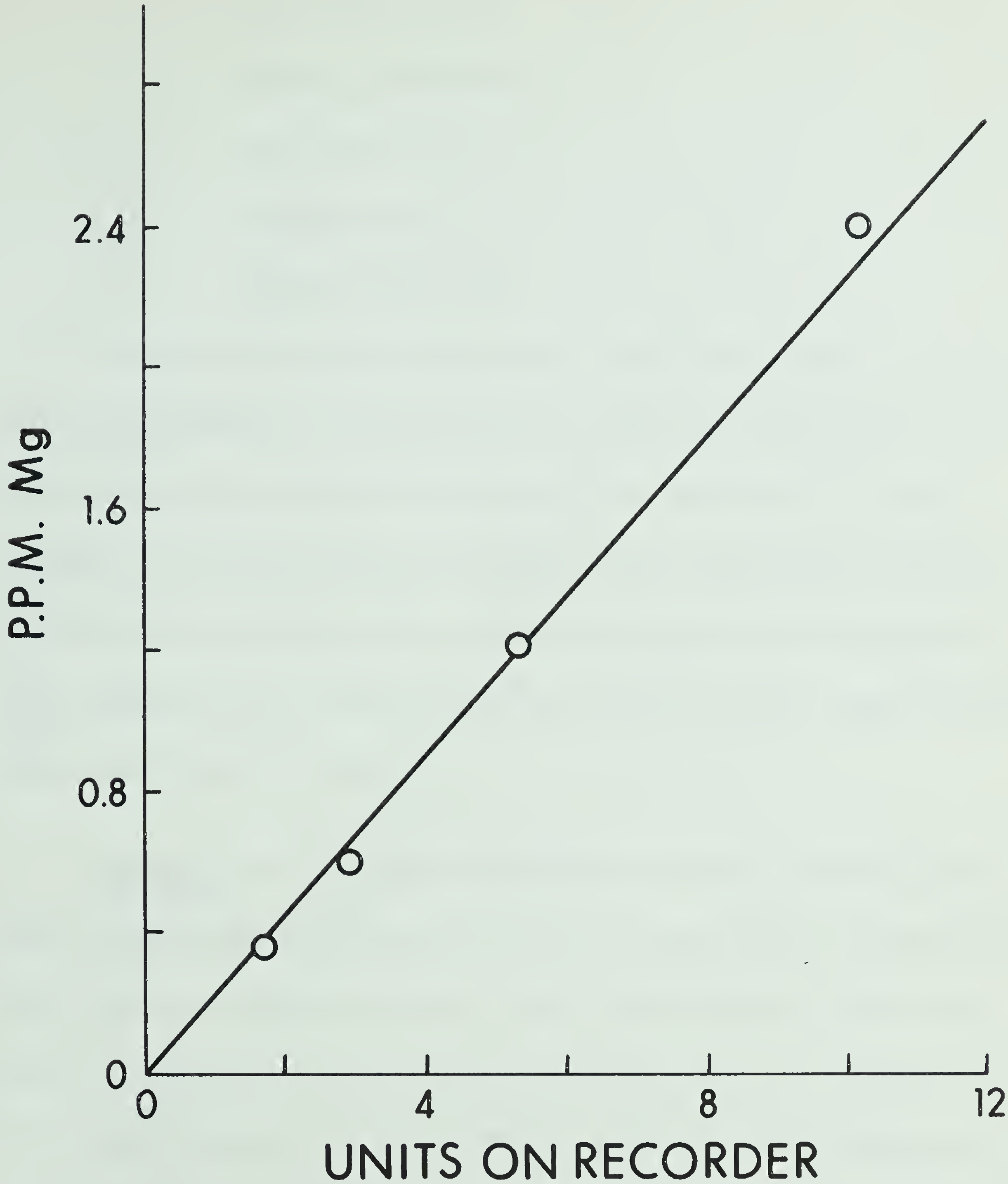

Figure 32. Curve for Conversion from Absorbance Values to ppm Mg

Flame setting 13.65

Element setting 209.5

Gas pressure 8 p.s.i.

Air pressure 40 p.s.i.

Source current 10 Ma

It was found that approximately 2 ppm. Mg was the greatest concentration that could be measured. This high sensitivity required that the samples be diluted until the Mg concentrations were below the 2 ppm. Mg level. Each sample was run between two standards using the settings stated above and standard operating procedures. The values for the diluted samples were then converted to ppm. Mg using the calibration curve and running standards, and then further converted to ppm. Mg present in the original undiluted samples.

Strontium: The Sr analyses were made on the atomic absorption spectrophotometer and the procedures followed were similar to those used for the Mg determinations. Four standards containing 4.90, 8.17, 13.07, and 16.34 ppm. Sr were made up and run on the spectrophotometer to obtain the working calibration curve shown in Figure 33. The settings used on the Model 290 atomic absorption spectrophotometer for the Sr analyses were the following:

Element control setting 530.2

Flame setting 13.80

Gas pressure 8 p.s.i.

Air pressure 40 p.s.i.

Source current 4 Ma

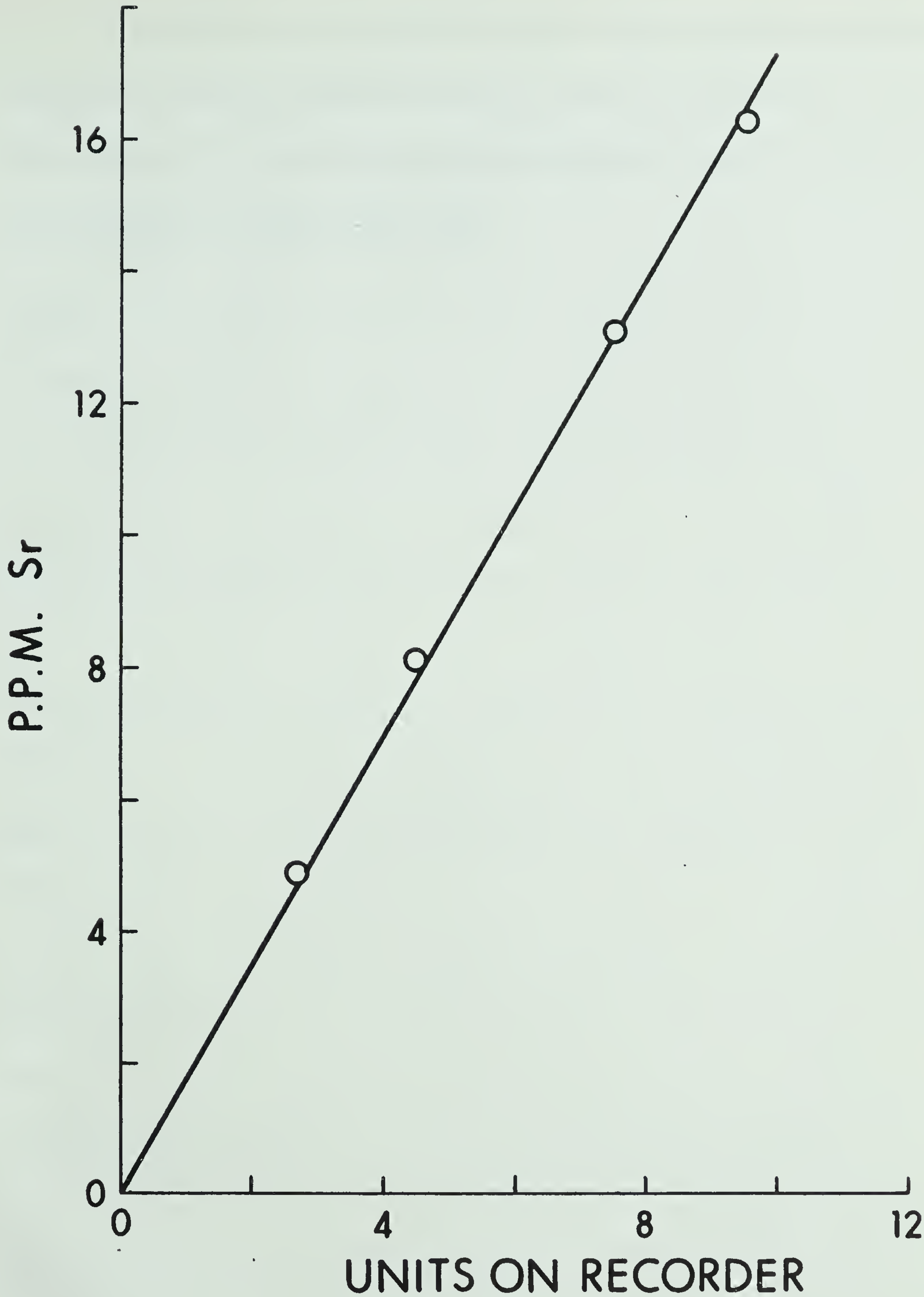

Figure 33. Curve for Conversion from Absorbance Values to ppm Sr

Each unknown was analysed for Sr using standard operating procedures and run between two of the analysed standards to check for instrument drift. The values obtained from the instrument graph were then converted to ppm. Sr using the calibration curve and running standard values.

APPENDIX III

Evaluation of Analyses

A large number of possible causes for experimental error exist in a study such as the present one. Care was taken to eliminate or minimize any personal errors that could be caused by such factors as poor sampling techniques, personal prejudice, inhomogeneity of samples, contamination of samples, loss of samples in weighing or analysis, etc.. It is felt that errors from these sources are negligible. Other sources of error arise largely from the technical limitations of the instruments employed in the actual analyses. Such factors as variations in power supply, positioning of x-ray peak, matrix and elemental interference, and detector limitations, etc., all tend to introduce experimental error. Also, charts and calibration curves can be read to only a limited degree of precision. Though it is impossible to measure the effect of all these errors directly, in most cases an estimate of their overall effect can be derived by calculating the standard deviation of the reference standard used. In the case of the x-ray fluorescence determinations, an analysed standard and three unknowns were determined together. This use of a "running standard" with the unknowns enabled statistical variations to be calculated and provided a check for instrument stability. Approximately fifty values on each standard run for the various elements were determined. Similarly, the Mg and Sr analyses made on the atomic absorption spectrophotometer, employed the use of a running standard that enabled estimation of the standard deviation. The Ni determinations which were made on the colorimetric spectrophotometer did not employ the use of a running standard. Rather, four standards of known amounts of Ni were analysed to produce a working calibration curve for the conversion of color

intensity to ppm. Ni. One standard, however, was repeated four times to give an estimation of the precision of the Ni determinations.

The values of standard deviation and precision for the various elements are tabulated in Table 10. Two standard deviations were used as the value for the precision. This means that 95 per cent of the time the determined values of the elements in the samples (when they are at approximately the level of concentration of the element in the standard) will differ from the true value by an amount equal to or less than two standard deviations. The per cent deviation given in Table 10 is merely the percentage the standard deviation is of the mean. The deviation of all the elements is less than 5 per cent except in the case of Mg determined by x-ray fluorescence. This high standard deviation for Mg is to be expected since this element is very hard to measure by fluorescence methods at such low levels of concentration. The limit of detectability used for the fluorescence analyses was three standard deviations of the background above the mean value of the background. That is to say, for an element peak to be detectable with 99 per cent confidence and not due to background variations, it must have a value at least as great as the background plus three standard deviations of the background.

The standards used for the construction of calibration curves and as external "running standards" were largely samples chemically analysed at the rock analysis laboratory at the University of Alberta, Edmonton. Two of these standards, R-84 and R-85, are chemically analysed samples from the Carson Creek North reef complex. Sample R-84 is from the reef facies of the Light Brown Member whereas R-85 represents a sample of the reef platform facies or the Dark Brown Member. The composition of the two standards is given in Table 11.

Table 10.- Standard Deviation And Precision Values for Geochemical Analysis

Standard Deviation and Precision for X-ray Fluorescence Standards

Constituent	Reference Standard	N	Amount Present	Mean of Analyses	Standard Deviation σ	% Deviation	Precision (2σ)
Sr	G-1	49	280 ppm	280 ppm	$\pm$6 ppm	2.14%	$\pm$12 ppm
S	R-66	51	1.30%	1.30%	.04%	3.08%	.08%
CaO	R-84	49	55.13%	55.15%	.24%	.44%	.48%
MgO	R-85	48	.83%	.83%	.14%	16.87%	.28%
MnO	R-85	50	.0075%	.0075%	.0001%	1.33%	.0002%
Fe_2O_3	R-85	52	.33%	.33%	.004%	1.22%	.004%
Al_2O_3	R-85	49	.31%	.30%	.006%	2.00%	.012%
SiO_2	R-85	50	1.03%	1.03%	.013%	1.26%	.026%

N = number of analyses used in calculation of standard deviation.

Standard Deviation and Precision for Spectrophotometer Standards

Constituent	Reference Standard	N	Amount Present	Mean of Analyses	Standard Deviation σ	% Deviation	Precision (2σ)
Ni	*	4	8.44 ppm	8.47 ppm	$\pm$ .20 ppm	2.36%	$\pm$ .40 ppm
Mg	*	30	1.20 ppm	1.184 ppm	$\pm$ .018 ppm	1.52%	$\pm$ .036 ppm
Sr	*	41	8.17 ppm	8.04 ppm	$\pm$ .40 ppm	5%	$\pm$ .8 ppm

*University of Alberta geochemical shelf standards for Ni, Mg, and Sr diluted to required concentrations.

N = number of analyses used in calculation of standard deviation.

Table 11. - University of Alberta Chemically Analysed Standards

ELEMENT	R-84 Reef facies limestone (Light Brown Member) PER CENT	R-85 Reef platform limestone (Dark Brown Member) PER CENT
SiO_2	.23	1.03
TiO_2	.02	.03
Al_2O_3	.08	.30
Fe_2O_3 FeO	.08	.33
MnO	.0038	.0075
MgO	.52	.83
CaO	55.13	53.38
Na_2O	.03	.08
K_2O	.01	.04
P_2O_5	.01	.02
H_2O	.08	.09
H_2O+	.66	1.93
CO_2	43.50	42.10
	100.35	100.17

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